EJFA Emirates Journal of Food and Agriculture

Emirates Journal of Food and Agriculture 37: 1–20
doi: 10.3897/ejfa.2025.168820

REVIEW ARTICLE

Applications of blockchain technology for enhancing traceability and food safety management in the beef supply chain

Jiaohui Tang[1]

1 *Department of Education, Graduate School, Kookmin University, Seoul, 02707, Republic of Korea*

Corresponding author: Jiaohui Tang (tangjiaohui6763@sina.com)

Academic editor: Ismet Boz ♦ **Received** 14 August 2025 ♦ **Accepted** 6 October 2025 ♦ **Published** 15 October 2025

Abstract

The globalization of agri-food supply chains has heightened consumer demand for transparency, accountability, and food safety, particularly in high-value sectors such as beef. Traditional centralized traceability systems face persistent challenges, including fragmented data, fraud risks, and delayed recall responses. Blockchain technology (BCT) emerges as a transformative solution, offering a decentralized, immutable, and transparent permissioned ledger capable of addressing these systemic weaknesses. This review comprehensively examines the application of BCT in the beef supply chain. Key findings indicate that blockchain's core attributes—decentralization, immutability, and a shared, auditable ledger—enable robust farm-to-fork tracking, deter food fraud, and accelerate targeted product recalls. Separately, when integrated with the Internet of Things (IoT) for automated, tamper-resistant data capture and with Artificial Intelligence (AI) for predictive analytics, deployments can further improve cold-chain assurance and enable early warning of spoilage or non-compliance. However, widespread adoption faces considerable hurdles, including technical challenges related to scalability and interoperability, economic considerations regarding implementation costs, organizational resistance to change, and the need for clear regulatory frameworks and industry-wide data standards. These constraints are often more acute in low- and middle-income countries, where smallholders face higher relative onboarding costs, gaps in digital infrastructure and standards, and limited institutional capacity for implementation. Drawing on established pilots—such as Walmart's IBM Food Trust deployment that reduced trace-back time from nearly seven days to 2.2 seconds, JD.com and Kerchin's QR-code-enabled beef traceability system for Chinese consumers, and JBS's blockchain-based Transparent Livestock Farming Platform for supplier monitoring—this review highlights blockchain's practical feasibility in real-world beef supply chains. Ultimately, blockchain offers a profound opportunity to enhance beef safety, quality, and trust, while also underscoring the need for concerted research efforts and multi-stakeholder collaboration to overcome barriers and fully realize its capabilities.

Keywords

beef supply chain, blockchain technology, food safety, food quality, fraud prevention, IoT, sustainability, traceability

Introduction

The global beef industry represents a significant sector in terms of economic contribution and its role in ensuring global food security. Concurrently, there is an escalating consumer-driven demand for comprehensive assurances regarding the safety, quality, and authenticity of beef products (Jo and Lusk 2023). This demand is largely fueled by an increased public awareness of foodborne diseases, with global health authorities documenting both the magnitude and specific attributions of risk. In the United States, CDC analyses identified 27 Salmonella outbreaks linked to beef during 2012–2019, underscoring beef's recurrent implication in outbreak investigations.

Copyright *Tang*. This is an open access article distributed under the terms of the Creative Commons Attribution License (CC-BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Regionally, EU surveillance records indicate on the order of ~5,000 reported foodborne outbreaks annually (across all foods), reinforcing the scale of the challenge. Attribution work by the Interagency Food Safety Analytics Collaboration (IFSAC) further shows that over 85% of *E. coli* O157 illnesses are attributed to vegetable row crops and beef combined, with beef representing one of the top implicated categories. These epidemiological patterns, together with rising consumer demand for production transparency, strengthen the case for robust traceability in beef supply networks (EIT Food 2023). Such complexity makes the establishment of robust traceability systems and the stringent management of food safety protocols not merely desirable but absolutely paramount. Failures in these critical areas can lead to devastating public health consequences, severe economic repercussions for the beef industry, including costly product recalls and loss of market access, and a profound and often lasting erosion of consumer trust (Patel et al. 2023). Recent empirical studies further nuance these dynamics, showing that blockchain-enabled traceability can shape perceived quality and, in some contexts, willingness-to-pay, while also indicating that traditional certification cues may at times dominate consumers' purchase decisions; together these findings underscore that trust effects are real but context-dependent (Treiblmaier and Garaus 2023, Reitano et al. 2024). The interconnectedness of globalisation and supply chain vulnerability is a critical consideration. As beef supply chains extend across national borders to meet global demand, they become inherently more fragmented and complex. This increased complexity, involving a greater number of handlers, processing steps, and transport links, directly multiplies the points at which food safety can be compromised or fraudulent activities can be introduced. Traditional traceability systems often struggle to cope with this scale and complexity, leading to data silos, a lack of interoperability between systems used by different stakeholders, and an inability to quickly and accurately link product information across disparate records. These systemic weaknesses create an environment where identifying the source of contamination or fraudulent products becomes a slow and arduous process, thereby increasing the risk of widespread food safety incidents and facilitating the perpetration of food fraud, such as the misrepresentation of product origin or quality. Consequently, the imperative for a more integrated, transparent, and secure system for managing information flow in the beef supply chain has never been more acute.

Conventional beef supply chains are beset by a multitude of challenges that undermine both their integrity and the confidence of consumers. High-profile food scandals serve as potent reminders of these vulnerabilities. For instance, the 2013 horsemeat scandal in Europe, where products labeled as beef were found to contain horsemeat, exposed significant failures in supply chain oversight and traceability. Comparable risks have been documented outside Europe. In Brazil, the 2017 'Operation Carne Fraca' investigation by federal authorities revealed systemic irregularities in major meat processors, including allegations of bribery, falsified inspection results, and the sale of meat unfit for consumption, which severely disrupted exports and trust in controls. In Asian markets, analyses of meat-fraud incidents have reported recurrent cases where chemically treated pork was sold as 'beef', illustrating how economic incentives can drive cross-species substitution and labeling deception. These incidents highlight the pervasive risk of food fraud, which can manifest in adulteration, origin mislabeling, false husbandry claims, or the intentional sale of lower-quality meat as premium grade (Duan et al. 2024). Such fraudulent activities are often driven by economic incentives but have severe consequences for consumer trust and public health, particularly when undeclared allergens or unsafe substances are involved. Beyond deliberate fraud, food safety incidents remain a persistent threat. Microbial contamination is a primary concern, with pathogenic bacteria such as Shiga toxin-producing *Escherichia coli* (STEC), *Salmonella* spp., and *Campylobacter* spp. frequently implicated in beef-related foodborne outbreaks. Contamination can occur at numerous points along the supply chain, from the farm environment and during slaughter and processing due to cross-contamination, to failures in temperature control during transportation and retail storage. The management of the cold chain is particularly critical for a perishable product like beef, and lapses can lead to rapid microbial growth and spoilage, increasing the risk of illness. Chemical hazards, including residues from veterinary drugs like antibiotics, pesticides from animal feed, or unintentional contamination from cleaning agents, also pose risks if not properly managed (Conter 2024).

The cumulative effect of these safety scares and fraudulent practices is a significant and often widespread erosion of consumer confidence in beef products and the industry as a whole. This trust deficit directly influences consumer purchasing decisions, with many consumers actively seeking greater assurances of safety and authenticity, or even reducing their consumption of products perceived as high-risk. Traditional traceability systems, often characterized by paper-based records or fragmented digital systems, have proven inadequate in comprehensively addressing these challenges, frequently failing to provide the timely, reliable, and transparent information needed to prevent incidents or rapidly respond when they occur (Moreira et al. 2021). This erosion of consumer trust translates into substantial economic ramifications for the beef industry, impacting brand loyalty, market share, and overall profitability. The potential for a technology to verifiably demonstrate product safety, authenticity, and ethical production practices is therefore not only a public health imperative but also a crucial economic driver for the sector (Lhermie et al. 2020). Blockchain technology, with its inherent characteristics of transparency and immutability, is increasingly being explored for its potential to restore this vital consumer trust by providing verifiable product information (Hidayati et al. 2023). However, blockchain cannot, by itself, guarantee the correctness of off-chain inputs; without robust data-capture, calibration,

and audit mechanisms, low-quality or falsified sensor and human-entered data may simply become immutably recorded ('garbage in, garbage out'), limiting the reliability of downstream assurances.

In response to the persistent challenges of opacity, fraud, and safety concerns within complex supply networks, blockchain technology (BCT) has emerged as a potentially transformative innovation (Reddy et al. 2021). Fundamentally, a blockchain is a type of distributed ledger technology (DLT) characterized by a growing list of records, termed blocks, that are securely linked together using cryptography. Each block typically contains a cryptographic hash of the previous block, a timestamp, and transaction data (Igwe et al. 2024). This design renders the data within the blockchain inherently resistant to modification; once recorded, a transaction cannot be retroactively altered without altering all subsequent blocks and achieving consensus from the network, a computationally impractical feat for most systems.

The core attributes of blockchain technology – decentralization, immutability, transparency (within permissioned frameworks), and enhanced security – directly address many of the data integrity and trust issues that plague conventional supply chain management systems (Igwe et al. 2024). By creating a shared, single version of truth accessible to authorized participants, blockchain can significantly enhance traceability, enabling products to be tracked from their origin through each stage of production, processing, and distribution to the final consumer. This heightened level of transparency and data integrity is posited to improve food safety protocols by allowing for rapid identification of contamination sources (Gadge et al. 2024), deter fraudulent activities by making illicit alterations to records exceedingly difficult, and ultimately contribute to rebuilding consumer confidence in the food system (Rebezov et al. 2024). Traditional food safety management systems are often reactive, primarily focusing on damage control and product recalls after a food safety incident has already occurred and potentially affected consumers. This reactive approach can be slow, costly, and inefficient in preventing widespread outbreaks or mitigating economic losses. Blockchain technology, by providing a platform for real-time, immutable data recording and sharing across the supply chain, offers a paradigm shift towards proactive food safety management. The ability to trace products and their ingredients with high precision and speed, as demonstrated in pilot projects where tracing times were reduced from days to mere seconds (Ma et al. 2024), allows for the early detection of potential safety issues. This enables preemptive actions, such as targeted recalls of specific batches rather than broad, wasteful recalls, and the rapid identification of the root cause of a problem (Gorman and Walls 2019). Such proactive capabilities not only enhance public health protection but also reduce economic losses and help maintain the operational integrity of the supply chain.

The primary aim of this review paper is to conduct a comprehensive analysis and synthesis of the existing body of literature concerning the applications of blockchain technology for the enhancement of traceability and food safety management specifically within the global beef supply chain. Fig. 1 presents a comprehensive framework illustrating how blockchain technology can transform the beef supply chain by enhancing traceability and food safety management. The scope of this review encompasses the entire beef value chain, from farm-level operations, including breeding and rearing, through transportation, slaughter, processing, distribution, and retail, to the final consumer. It will critically examine various facets of blockchain implementation, including the underlying technological principles, diverse application models, and the synergistic integration of blockchain with complementary technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI). Furthermore, the review will explore the economic implications, including cost-benefit analyses and return on investment considerations, the perspectives and adoption challenges faced by various stakeholders, the current regulatory landscape, and ongoing standardization efforts. A significant portion of the review will be dedicated to analyzing reported case studies and pilot projects to distill practical outcomes and lessons learned. The rationale for undertaking this comprehensive review stems from the confluence of several factors. Firstly, there is a rapidly escalating interest within both academia and the food industry in leveraging blockchain technology to address persistent challenges in food supply chains, as evidenced by a growing volume of research and pilot implementations. Secondly, the beef supply chain, due to its complexity, global nature, high economic value, and susceptibility to food safety and fraud risks, presents a particularly compelling case for the application of advanced traceability solutions. A consolidated and critical assessment of blockchain's potential, its progress to date, and the inherent pitfalls in this specific context is therefore timely and necessary. This review seeks to provide a nuanced understanding of how blockchain can contribute to a safer, more transparent, and more trustworthy beef supply chain, while also identifying knowledge gaps and areas requiring further investigation.

The beef supply chain: Complexities, traceability deficiencies, and food safety imperatives

Anatomy of the Modern Beef Supply Chain

The modern beef supply chain is a complex, multi-stage network responsible for transforming live cattle into the diverse range of beef products available to consumers globally. Understanding its intricate structure is fundamental to appreciating the challenges associated with traceability and food safety management. The journey typically commences at the farming and production stage. This phase encompasses a variety of practices, including

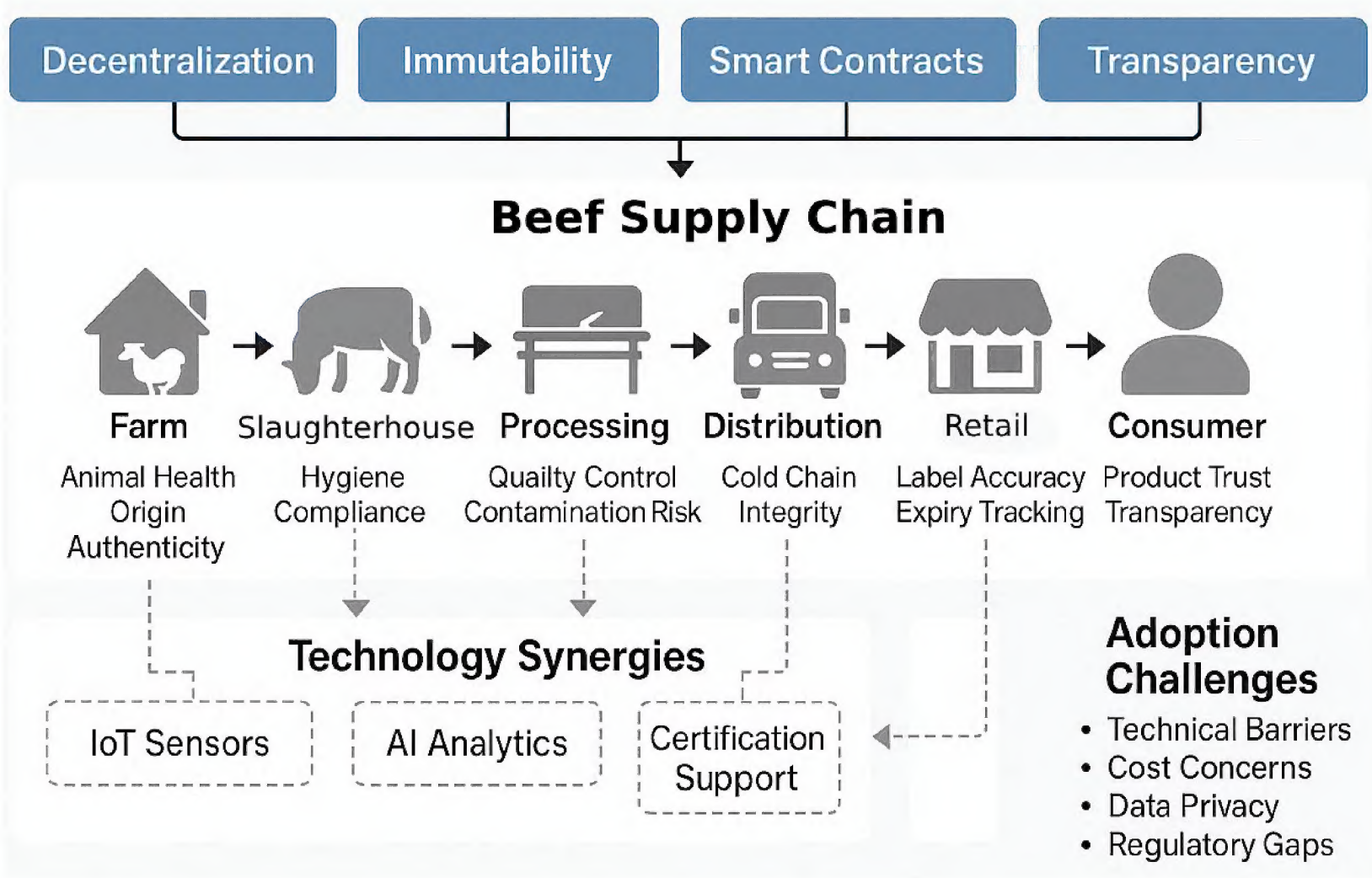

Figure 1. Blockchain-enabled transformation framework for the beef supply chain, illustrating critical stages from farm to consumer alongside key risks and traceability requirements.

cattle breeding, which may involve natural mating or artificial insemination, often with a focus on specific genetic traits for meat quality or production efficiency (Team 2017). Cow-calf operations form the backbone of this stage, where herds of cows are maintained to produce calves annually. These calves are then reared through distinct growing and 'finishing' phases. The finishing phase, in particular, often involves an intensive feeding period designed to achieve optimal market weight and carcass characteristics prior to slaughter. These rearing activities can occur on a single farm or involve the movement of cattle between multiple specialized farms or feedlots. Beef originates from both suckler herds, specifically bred for beef production, and from the dairy sector, where male calves or culled cows contribute to the beef supply.

Following the production phase, cattle are transported to abattoirs or processing facilities (Borders et al. 2024). This movement can occur via auction markets, where cattle are bought and sold by various players, or through direct sales contracts between farmers and processors. Third-party livestock agents or brokers may also facilitate these transactions. The slaughter and processing stage is a critical control point in the supply chain. Here, animals are humanely slaughtered (Broom 2021), and carcasses are dressed and chilled (Oyan et al. 2024). Subsequently, these carcasses are broken down into primal cuts, sub-primal cuts, and further processed into a wide array of beef products, including minced beef, sausages, and ready-to-eat meals. This processing can take place in large, integrated facilities that handle all operations from slaughter to packaging, or it may involve several specialized plants. The complexity of traceability is significantly increased when dealing with multi-ingredient processed beef products or when beef is transported as a bulk commodity, such as trimmings for grinding, as tracking individual source components becomes more challenging.

Once processed and packaged, beef products enter the distribution network (Endoh et al. 2021). Processors supply domestic markets through two primary channels: the retail market, which includes supermarkets, hypermarkets, independent butchers, and online retailers where consumers make their purchases; and the wholesale/food service market, which supplies beef to restaurants, fast-food chains, hotels, catering services, and other institutional buyers. For international markets, processors export beef products to importers in other countries (Chatellier 2021). These importers then undertake further distribution to retailers and food service establishments within their respective regions. The increasing globalization of the beef trade and market liberalization has led to longer and more intricate supply chains, often involving multiple border crossings and diverse regulatory environments. This international dimension adds layers of complexity to logistics, quality assurance, and traceability. Many countries, including major beef producers, also rely on imports to supplement domestic production, ensure year-round availability, or meet specific market demands for particular cuts or quality grades (Gaynutdinov et al. 2021). For example, the UK beef supply chain is estimated to be approximately 75% self-sufficient, with imports playing a crucial role in meeting the remaining 25% of domestic demand and providing resilience against shocks such as animal disease outbreaks. Fig. 2 summarises the beef supply chain stages and the associated identifiers, data carriers, and Critical Tracking Events (CTEs), clarifying where data are generated, transformed, and handed off across organisations.

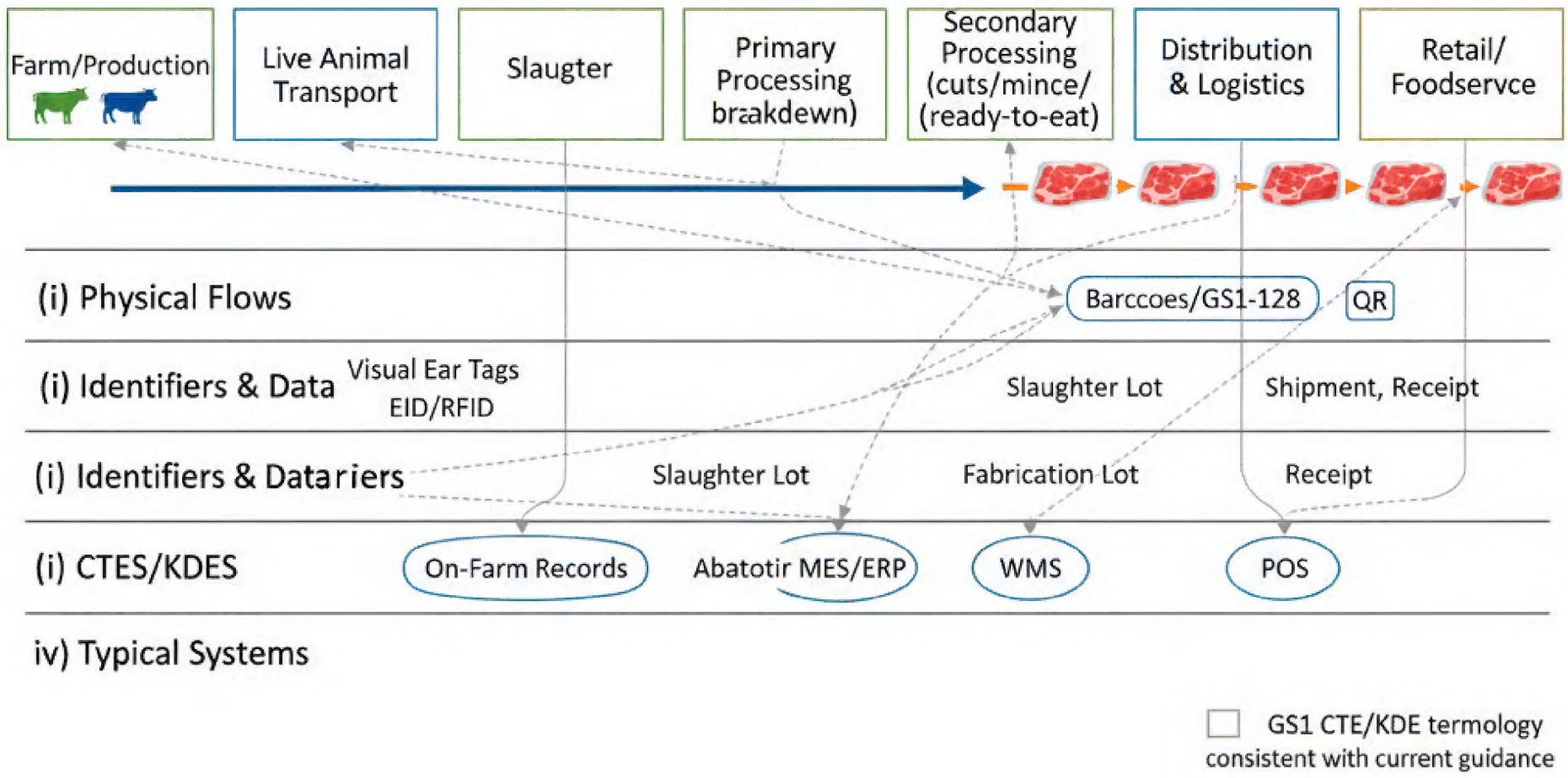

Figure 2. Beef supply chain stages and traceability data flows.

Beyond these primary stages, a host of supporting sectors are integral to the functioning of the beef supply chain. These include feed manufacturers and suppliers, veterinary services providing animal health care, pharmaceutical companies supplying medicines and vaccines (Cohen 2022), equipment manufacturers, logistics and transportation providers specializing in refrigerated transport, and regulatory agencies overseeing food safety and trade. While not always directly handling the beef product, these ancillary players generate critical data and influence the overall safety and traceability of the final product. The sheer number of actors and the diversity of operations at each stage contribute to the fragmented nature of many beef supply chains, posing significant challenges for end-to-end visibility and data integration.

Prevailing traceability systems

Traceability systems are indispensable for modern food supply chains, particularly for high-risk commodities like beef. They are designed to track the movement of products and their attributes from origin to consumption, facilitating product recalls, ensuring regulatory compliance, and providing consumers with information about the food they purchase. In the beef industry, a variety of traceability methods are currently employed, ranging from traditional paper-based systems to more technologically advanced solutions. Commonly used identification tools include alphanumerical codes, standardized barcodes such as GS1-128, and Radio Frequency Identification (RFID) tags. RFID tags, for instance, can be attached to individual animals or product batches, allowing for automated data capture at various checkpoints using RFID readers. These systems primarily focus on tracking products through the distribution and warehousing stages of the supply chain. Some systems utilize biometric identifiers for live animal traceability from farm to slaughter, or DNA barcoding on product packaging for origin verification.

Despite these capabilities, prevailing traceability systems in the beef supply chain suffer from several inherent limitations that compromise their effectiveness (Moreira et al. 2021). A primary issue is their often centralized, fragmented, and opaque architecture. Data is frequently stored in disparate, proprietary databases controlled by individual companies, leading to information silos. This lack of interoperability makes it exceedingly difficult to share data seamlessly and create a cohesive, end-to-end traceability record across different stakeholders in the supply chain (Oriekhoe et al. 2024). Consequently, linking product information from farm to fork can be a slow, manual, and error-prone process. This fragmentation results in an inability to comprehensively link records, inaccuracies and errors in the data, and significant delays in accessing essential information, particularly during food safety crises or recall events. To contextualise technology choices, we compared typical costs. Barcodes/GS1-128 remain the least-cost option for case/pallet identification; recent surveys report per-label media costs around US$0.02 with entry-level printers/scanners in the low hundreds of US$ range, although total cost depends on throughput and software integration (Liu et al. 2023). RFID/EID for cattle introduces higher unit and capital costs but enables contactless, line-speed capture: official electronic ear tags in U.S. cattle currently cost roughly US$0.70–3.65 per head, with some programmes subsidising or providing tags at no cost; handheld/panel readers for livestock typically range from ~US$900–1,750 and market studies of auction facilities report total installations from ~US$5,250 to US$63,000, depending on lanes and speed-of-commerce

requirements. DNA-based verification/trace-back offers product-level authentication but incurs laboratory expenses per sample; prices vary by method and service model, from ~US$6 per sample for high-throughput real-time PCR in controlled lab workflows to ~US$165 per sample for forensic-grade species ID services, with commercial end-to-end programmes (e.g., DNA TraceBack®) negotiated at enterprise scale (Castanon et al. 2025).

A fundamental deficiency in many traditional systems is the lack of robust mechanisms to verify the trustworthiness of the information shared by different supply chain participants (Oriekhoe et al. 2024). These systems often operate on a basis of assumed trust, without independent validation of the data entered. This vulnerability can be exploited for fraudulent purposes, such as misrepresenting product origin (Nehal et al. 2021), quality attributes, or safety certifications. Furthermore, the traceability coverage is often incomplete, with many systems primarily focusing on downstream activities like distribution and warehousing, while neglecting crucial upstream stages such as on-farm practices, animal feed, or detailed processing information. The "one step forward, one step back" traceability capability, common in many industries, is often insufficient for the rapid and precise trace-back required in complex food supply chains like beef, especially when facing urgent food safety issues (McLachlan 2022).

The integrity of any traceability system, regardless of its technological sophistication, is fundamentally dependent on the quality of the data input at the source. This leads to the critical challenge of "garbage in, garbage out" (GIGO) (Zhang et al. 2023). If inaccurate, incomplete, or deliberately falsified data is entered into the system at any point, the entire traceability record becomes compromised, even if the system itself is secure against subsequent tampering. This underscores the need for robust data validation mechanisms at the point of entry and highlights a limitation that technology alone cannot solve without strong governance and reliable data capture methods. Moreover, the implementation and maintenance of some advanced traditional traceability systems can be costly, particularly for smaller producers or businesses in developing countries, creating an uneven playing field and potential gaps in overall supply chain visibility (Caveen et al. 2021). Finally, centralized databases are inherently more vulnerable to single points of failure, data breaches, and malicious tampering or falsification of records compared to decentralized architectures. These limitations collectively diminish the reliability of current traceability efforts and underscore the need for more resilient, transparent, and trustworthy solutions (Fu et al. 2025).

The "trust gap" in data sharing represents a significant impediment (Piorkowski et al. 2021). The beef supply chain is composed of diverse, often competing, entities. In such an environment, there can be a reluctance to share commercially sensitive information, or a lack of incentive to ensure the accuracy of data shared with other parties, especially if there is no independent verification or shared benefit. Traditional systems, being often monopolistic or asymmetric in terms of information control, can exacerbate this issue. Without a trusted, neutral platform for data exchange, information remains fragmented and its integrity questionable. This systemic lack of trust in shared data is a primary enabler of both food safety lapses and fraudulent activities, as it becomes difficult to establish a verifiable and universally accepted history of the product. To visually summarize the challenges associated with existing traceability systems in the beef industry, Fig. 3 presents an integrated overview of commonly used technologies and their critical limitations.

Critical food safety hazards and management challenges

The beef supply chain is susceptible to a range of food safety hazards that can compromise public health and consumer confidence if not effectively managed. Microbial contamination stands out as one of the most significant risks (Adjei et al. 2022). Pathogenic bacteria such as Shiga toxin-producing *Escherichia coli* (STEC), notably *E. coli* O157:H7, Salmonella spp. (Havelaar et al. 2022), and Campylobacter spp. are frequently associated with beef products and can cause severe foodborne illnesses. Contamination can originate from various sources throughout the chain: on the farm, cattle may carry these pathogens in their gastrointestinal tracts (Cohen 2022); during slaughter, fecal contamination of carcasses can occur if hygiene practices are inadequate; and cross-contamination can happen during processing, cutting, and grinding operations. Further microbial growth can occur during distribution, retail, and even in the consumer's home if temperature control and handling practices are improper (Tarawneh et al. 2024).

Temperature abuse is another critical factor influencing beef safety and quality (Schwartz et al. 2022). Beef is a perishable product that requires strict temperature control throughout the cold chain to inhibit microbial growth and slow down spoilage processes. Deviations from recommended temperature ranges during transportation, storage at distribution centers, retail display, or in food service establishments can lead to a rapid increase in bacterial loads, potentially rendering the product unsafe for consumption even before its expiry date. Real-time monitoring of temperature and humidity is therefore crucial for maintaining the integrity of the cold chain (Cil et al. 2022).

Chemical hazards also pose a risk in beef production. These can include residues from veterinary drugs, such as antibiotics, growth promoters, or anti-parasitic treatments, if withdrawal periods are not strictly adhered to before slaughter (Conter 2024). Pesticide residues may be present in animal feed, which can then accumulate in the animal's tissues. Contamination can also occur from environmental sources or from the improper use of cleaning and sanitizing agents in processing facilities. The presence of such chemical residues above permissible limits can have adverse health effects on consumers.

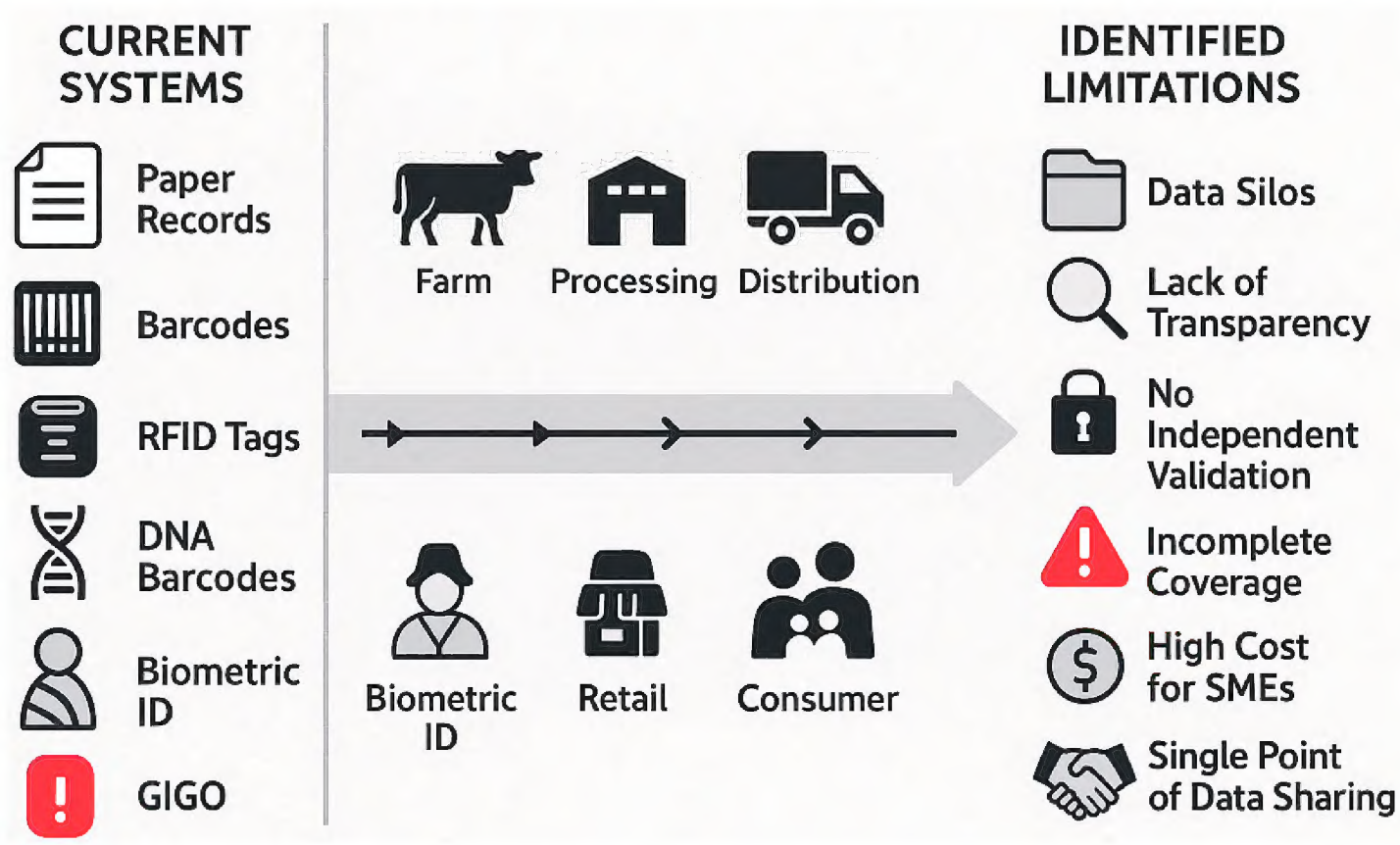

Figure 3. Limitations of prevailing beef traceability systems and their impact on supply chain transparency

Physical contaminants, such as metal fragments from equipment, plastic, or glass, though less common, can also enter the food supply during processing and handling, posing an injury risk. Antimicrobial resistance (AMR) is an emerging cross-cutting hazard in beef supply chains. Surveillance systems in the EU, North America, and globally continue to detect resistant Salmonella, Campylobacter, and indicator *E. coli* in food-producing animals and retail meats, with trends varying by geography and species. Recent harmonised EU monitoring (2022–2023) reported concerning resistance patterns in zoonotic bacteria from cattle and derived meats; Canada's CIPARS indicates generally low and stable resistance in bovine *E. coli* alongside increases in Campylobacter resistance in certain components; and WHO-GLASS underscores the broader public-health burden and the need for integrated One-Health actions. Incorporating AMR into hazard analysis strengthens the case for timely, interoperable traceability—linking on-farm antimicrobial use records with downstream lot history to support source attribution and risk management (Authority and European Centre for Disease Prevention and Control 2025).

Food fraud and adulteration, as previously discussed, represent a significant challenge that also intersects with food safety (Khan et al. 2023). The intentional substitution of beef with cheaper or unapproved meats, the misrepresentation of origin or quality attributes (Afzaal et al. 2022), or the use of unapproved additives can introduce unknown safety risks, especially if the substituted ingredients are allergenic or carry specific pathogens (Modi et al. 2021).

Managing these diverse hazards effectively is complicated by the inherent characteristics of the beef supply chain: its length, complexity, and the multitude of stakeholders involved. Lack of end-to-end visibility makes it difficult to pinpoint the exact source of contamination or non-compliance quickly. Ensuring consistent adherence to food safety standards (such as Hazard Analysis and Critical Control Points - HACCP principles, Good Agricultural Practices - GAP, and Good Manufacturing Practices - GMP) across all entities, from large multinational corporations to small-scale farmers and processors, is a continuous challenge. The high cost and logistical complexity of traditional product recall mechanisms further underscore the urgent need for more efficient, transparent, and proactive food safety management systems. The extended and often global nature of beef supply chains means that a single food safety failure at any point – the "weakest link" – can have widespread and severe consequences, affecting numerous downstream businesses and a large consumer base. The longer and more fragmented the chain, the more potential weak links exist, and the more difficult it becomes to manage risks effectively using conventional approaches.

While individual stakeholders within the beef supply chain may diligently collect substantial amounts of data for their internal operational needs and compliance, the overall system often suffers from being "information poor" when it comes to comprehensive, end-to-end traceability and holistic risk assessment. This paradox arises from the lack of standardization in data formats, the absence of interoperable systems for data exchange between different entities, and the pervasive trust gap that discourages open sharing of potentially sensitive information. Data may be abundant in isolated silos but inaccessible or unusable for creating a unified, verifiable history of a product's journey. This situation highlights the critical need for a technological framework that not only facilitates data recording but also ensures its standardization, integration, validation, and secure sharing among all authorized participants across the entire beef supply chain.

The following table (Table 1) summarizes the key stages, common traceability deficiencies, and major food safety risks prevalent in the conventional beef supply chain, providing a structured overview of the challenges that blockchain technology aims to address.

Table 1. Key stages, traceability deficiencies, and food safety risks in the conventional beef supply chain.

Stage of Supply Chain	Key Activities/Operations	Common Traceability Methods Used (if any)	Key Traceability Deficiencies/ Challenges at this Stage	Major Food Safety Hazards/ Risks at this Stage	Opportunities for blockchain intervention
Farm/ Production	Cattle breeding, calving, rearing (cow-calf, backgrounding, finishing), feeding, animal health management (vaccinations, treatments), record-keeping.	Ear tags (visual, electronic/ RFID), paper records, farm management software.	Inconsistent record-keeping, lack of standardized data, difficulty linking individual animal data through multiple farm movements, potential for unrecorded treatments, GIGO if data entry is manual/inaccurate.	Zoonotic diseases (e.g., *Brucellosis*), antibiotic residues, pesticide residues in feed, microbial contamination from environment (e.g., *E. coli*, *Salmonella* in feces).	mmutable recording of animal birth, treatments, and antimicrobial use as signed events linked to animal ID (visual/ RFID), enabling auditable AMU histories and selective withdrawal verification.
Live Animal Transport	Loading, transportation of cattle to auctions, other farms, or slaughterhouses, unloading.	Movement documents, vehicle logs, sometimes RFID scanning at checkpoints.	Stress on animals affecting meat quality and susceptibility to disease, potential for commingling of animals from different sources without clear segregation, lack of continuous monitoring of animal welfare or transport conditions.	Spread of infectious diseases, injury to animals, heat stress or cold stress affecting welfare and potentially meat quality.	Time-stamped movement events (loading, border crossings, lairage receipt) with verifiable credentials for hauliers; automated reconciliation with EID reads to reduce missing moves.
Slaughter	Stunning, bleeding, skinning, evisceration, carcass splitting, inspection (ante-mortem and post-mortem).	Carcass tags, lot identification, government inspection records.	Difficulty linking live animal records to specific carcasses accurately and consistently, potential for errors in manual tagging/recording, challenges in tracing back specific issues identified post-mortem to the farm of origin rapidly.	Microbial contamination of carcasses (e.g., *E. coli*, *Salmonella*) from hide, feces, or environment; cross-contamination between carcasses; residues of veterinary drugs or contaminants if not detected.	Lot creation and carcass ID anchoring to pre-slaughter movement history; hashed HACCP/CCP checks (e.g., hide removal, evisceration) to support targeted recalls.
Primary Processing	Carcass chilling, aging, cutting into primal/sub-primal cuts, deboning, trimming, packaging of fresh cuts.	Lot numbers, barcodes on packaged products, internal processing records.	Loss of individual animal identity if batching occurs early, difficulty in tracing specific cuts back to a single animal if commingled, ensuring accurate labeling of cuts, GIGO in batch records.	Microbial growth if chilling/ aging temperatures are not controlled, cross-contamination during cutting and deboning, survival of pathogens on equipment or surfaces.	Lot split/merge provenance graphs; on-chain attestations for sanitation/CIP cycles; linkage to pathogen test results with privacy-preserving aggregation.
Secondary Processing/ Value-Adding	Grinding, marinating, cooking, formulation of multi-ingredient products (e.g., sausages, ready meals), packaging.	Batch codes, ingredient lot tracking (often manual or disparate systems).	Extreme complexity in tracing ingredients in multi-component products, reliance on supplier information for ingredient traceability, potential for mislabeling or undeclared allergens, difficulty in verifying claims (e.g., "100% beef").	Introduction of allergens, survival or growth of pathogens during processing, contamination from other ingredients or processing environment, chemical hazards from additives or packaging.	Recipe/batch declarations and allergen controls anchored to inbound lots; automated FSMA/ Reg. (EC) 178/2002 compliance evidence during recalls.
Distribution/ Logistics	Storage (chilled/frozen), transportation via road, rail, sea, or air to distribution centers, wholesalers, or directly to retail/food service.	Pallet labels, case barcodes (e.g., GS1-128), shipping documents, temperature loggers (sometimes).	Breaks in the cold chain during transit or storage, lack of real-time temperature monitoring for all shipments, difficulty in tracking exact location and conditions of products in real-time, data fragmentation between different logistics providers.	Temperature abuse leading to microbial growth and spoilage, physical damage to packaging compromising product integrity, cross-contamination if mixed loads are not handled properly.	Smart-contract checks on temperature excursion telemetry and chain-of-custody handoffs; exception alerts tied to lot provenance.
Retail/Food Service	Receiving, storage, display (retail), preparation and cooking (food service), sale to consumer.	Date codes on products, internal stock rotation systems, some point-of-sale data.	Inconsistent stock rotation (FIFO/FEFO), potential for temperature abuse in display cases or storage, mislabeling at point of sale (e.g., re-packaging), limited traceability information available to consumers.	Microbial growth due to improper storage or display temperatures, cross-contamination during food preparation (food service), survival of pathogens if undercooked.	Consumer-facing verifiable QR for origin and welfare claims; selective disclosure of sustainability metrics; post-market complaint linkage to specific lots for rapid root-cause analysis.

Blockchain technology in generic supply chain applications

Smart contracts: Automating supply chain processes and agreements

A significant innovation enabled by many blockchain platforms is the concept of smart contracts (Hewa et al. 2021). These are self-executing computer programs where the terms of an agreement between two or more parties are directly written into lines of code (Wüst et al. 2020). Smart contracts reside on the blockchain and automatically execute predefined actions when specific conditions, also coded into the contract and verified by data on the blockchain, are met (Song et al. 2021). This automation can streamline numerous supply chain processes and enforce agreements without the need for traditional intermediaries (Farokhnia and Kafshdar Goharshady 2023).

In the context of supply chain management, smart contracts can be programmed to trigger various actions based on verifiable events. For example, a smart contract could automatically release payment to a supplier once the blockchain receives confirmation (e.g., from an IoT sensor or a verified manual entry) that a shipment has been delivered and that quality parameters (such as temperature during transit) have been maintained within acceptable

limits (Kaur et al. 2022). Similarly, smart contracts can manage inventory levels by automatically triggering reorder requests when stock falls below a certain threshold. They can also facilitate regulatory compliance by automatically checking if necessary certifications are in place or if specific procedures have been followed, logging these checks on the blockchain for audit purposes. If deviations from agreed-upon terms or safety protocols occur, such as a temperature breach in a cold chain shipment, a smart contract could automatically trigger alerts to relevant parties, initiate penalty clauses, or prevent further movement of the affected product until corrective action is taken.

The use of smart contracts offers several advantages (Hewa et al. 2021, Khan et al. 2021). By automating processes, they can significantly reduce manual intervention, which in turn minimizes the risk of human error (Alharbi et al. 2024), reduces administrative overhead (Omar et al. 2020, El Khatib et al. 2023), and speeds up transaction times (Jamil et al. 2021). The conditions of the smart contract are transparent to the participating parties (within the permissioned framework) (Lucas et al. 2021) and, once deployed on the blockchain, are immutable (Kaushal et al. 2021). This reduces ambiguity (Yadav et al. 2022) and the potential for disputes, as the execution of the contract is based on objective, verifiable data recorded on the shared ledger.

Beyond mere efficiency gains, smart contracts on a blockchain can foster a "trustless" environment for executing agreements. The term "trustless" in this context does not imply a lack of trust, but rather that trust is shifted from intermediaries or individual parties to the blockchain protocol and the code of the smart contract itself (Anglen 2023). Because the execution is automated and based on data that is cryptographically secured and agreed upon by consensus, parties can have greater confidence that the terms of their agreement will be fulfilled as specified, without relying on a central authority to enforce them. This capability is particularly valuable in complex, multi-party supply chains where establishing and maintaining trust between all actors can be challenging. By reducing counterparty risk and the need for intermediaries to verify and execute transactions, smart contracts can lead to more efficient, secure, and reliable supply chain operations.

Enhancing end-to-end traceability in the beef value chain

Blockchain technology provides the infrastructure for creating a comprehensive and reliable traceability system that can follow beef products through every stage of their complex journey. This end-to-end visibility is crucial for ensuring authenticity, quality, and safety. To visualize the application of blockchain technology across the beef supply chain, Fig. 4 presents a comprehensive end-to-end traceability framework.

At the very beginning of the supply chain, blockchain can be used for animal identification and provenance tracking. Unique identifiers for individual animals, captured through methods like RFID tags or even biometric data, can be registered on the blockchain along with critical information such as date and farm of birth, breed details, and genetic lineage (Adesiyan 2025). This creates an immutable foundational record for each animal, serving as the starting point for its traceable history.

As animals are raised, crucial data regarding feed and medication records can be logged onto the blockchain. This includes details about the type and source of feed, which is essential for verifying claims such as "grass-fed" or "non-GMO fed" (Conter 2024). Similarly, records of all veterinary treatments, including vaccinations and any antibiotic use (along with withdrawal periods), can be immutably stored (Conter 2024). This provides verifiable evidence for "antibiotic-free" claims and supports animal health monitoring.

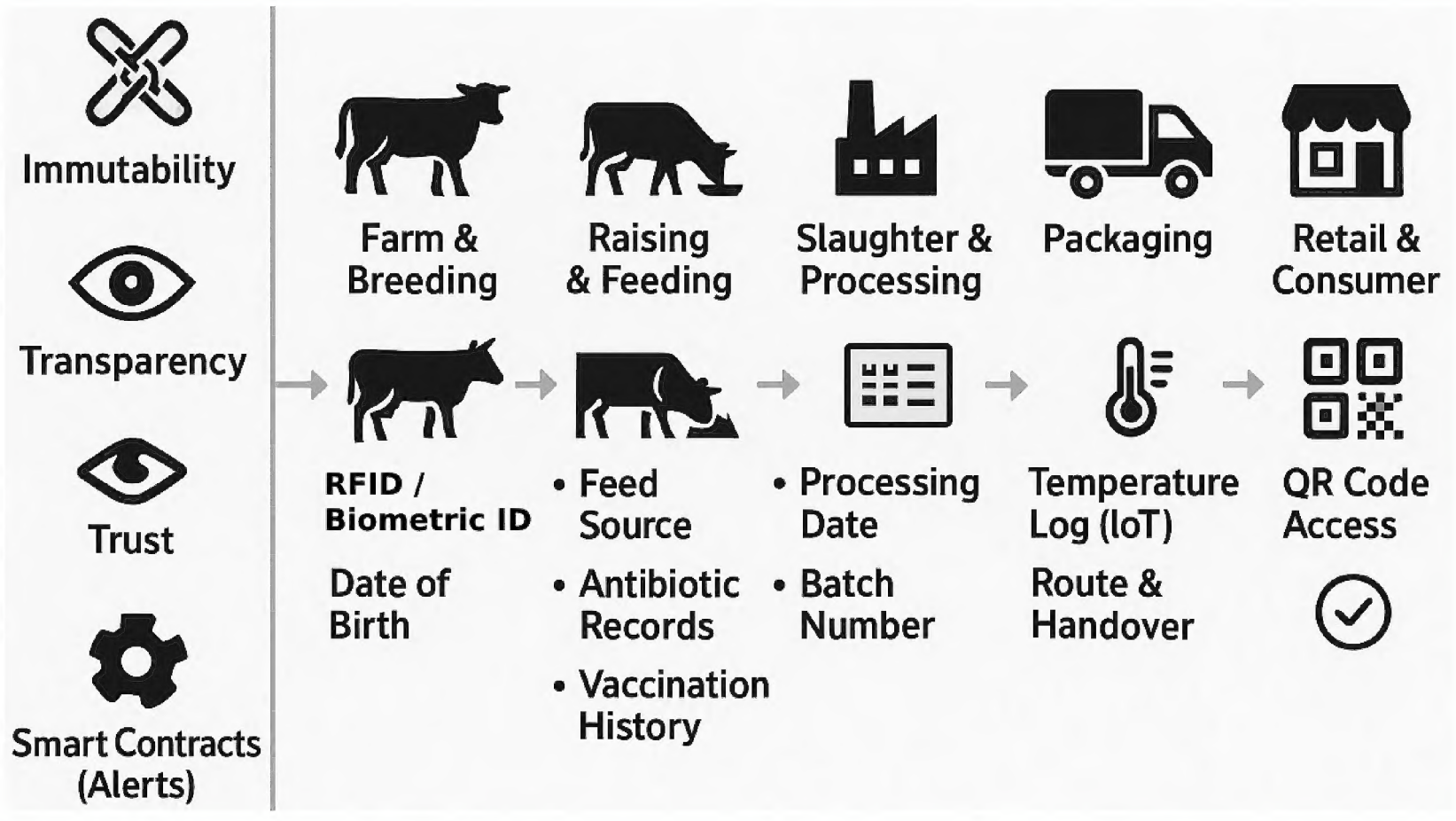

Figure 4. Blockchain-enabled end-to-end traceability framework for the beef supply chain.

Traceability must be seamlessly maintained as the animal moves through slaughter, processing, and packaging. Blockchain enables the linking of live animal data (from its unique identifier) to the corresponding carcass data after slaughter. Subsequently, information such as processing dates, batch numbers for processed meat (e.g., primal cuts, ground beef), and packaging details can be added to the blockchain record associated with that animal or batch. This ensures that as the product changes form, its traceable history remains intact and verifiable.

When fresh beef is subjected to commingling operations such as grinding, marination or the manufacture of multi-ingredient products, the one-to-one linkage between a single animal and a finished unit can be lost. Blockchain does not by itself recreate physical identifiers after commingling, but it supports layered technical and procedural measures that preserve and verify batch provenance. Practical strategies include (i) rigorous lot/case-level labelling using GS1 lot identifiers and continuous chain-of-custody recording at every handover (mass-balance accounting), (ii) recording declared input-lots and their proportional contributions to output batches in on-chain metadata (so that forward and backward tracing can be performed at the batch level), (iii) anchoring laboratory verification results (e.g., DNA profiles, stable isotope, or trace-element fingerprints) as hashes on the blockchain to provide off-chain, tamper-resistant verification evidence, and (iv) embedding smart-contract rules that require supplier attestations and limit acceptable mixing thresholds. These combined measures allow blockchain systems to narrow suspect batches rapidly and to provide verifiable evidence for recalls. Pilot projects and applied research show the feasibility of such approaches in red meat systems: BeefLedger demonstrated QR-code case-level provenance anchored on chain for Australian beef supply chains (BeefLedger, QUT Design Lab (McQueenie et al. 2024)), and laboratory-based methods to identify the batch-of-origin of mixed-meat products using DNA profiling and statistical inference have been developed and validated . Together, operational mass-balance recording on blockchain plus periodic laboratory verification constitute a practical and evidence-based approach for addressing identity loss in processed beef.

The transportation and cold chain monitoring phase is critical for perishable products like beef (Onwude et al. 2020, Awad et al. 2021). Blockchain can record vital logistics data, including details of transport companies, routes taken, and handover points (Akkerman et al. 2022). More importantly, when integrated with IoT sensors, real-time data on environmental conditions such as temperature and humidity during transit and storage can be continuously logged onto the blockchain (Chen et al. 2022). This provides an immutable record of cold chain integrity, crucial for ensuring both safety and quality. Smart contracts can be programmed to issue alerts if temperature deviations occur (Gokul Prasad et al. 2023).

Finally, at the retail and consumer access point, blockchain-derived traceability information can be made available to end-users (Wang et al. 2021). This is often facilitated through QR codes printed on product packaging (Khanna et al. 2022). By scanning the QR code with a smartphone, consumers can potentially access a wealth of information about the beef product's journey, including its farm of origin, processing details, and any certifications (Lafargue et al. 2022). This empowers consumers to make more informed purchasing decisions and fosters a greater sense of trust in the product and brand (Ngo et al. 2020).

Bolstering food safety management and fraud prevention

The enhanced traceability enabled by blockchain technology directly translates into significant improvements in food safety management practices and provides powerful tools for combating food fraud in the beef supply chain. One of the most critical food safety benefits is the creation of immutable audit trails for compliance. Every event, transaction, and safety check performed along the supply chain can be recorded on the blockchain, creating a tamper-proof and time-stamped digital log (Wahyuni et al. 2024). This includes records of adherence to food safety protocols like Hazard Analysis and Critical Control Points (HACCP), Good Agricultural Practices (GAP), and Good Manufacturing Practices (GMP). Such comprehensive and verifiable audit trails greatly simplify the process of demonstrating compliance to regulatory authorities and facilitate more efficient internal quality control audits. The integrity of these records reduces the likelihood of fraudulent compliance claims. For example, Walmart's Food Trust proofs-of-concept with IBM demonstrated a practical, operational example of dramatic traceability speed-up: a benchmark tracing exercise for a packet of sliced mangoes that took almost seven days to resolve under conventional procedures was reduced to approximately 2.2 seconds using the blockchain-based system, illustrating how rapid, end-to-end digital traceability can materially accelerate recall and containment actions (Kamath; IBM Food Trust / Walmart documentation) (Kamath 2018). The mango pilot (and subsequent Walmart pilots including pork and other produce) became a touchstone example in the sector for how an appropriately designed, permissioned ledger plus supplier onboarding can reduce investigation and recall lead times in practice. The mango and pork pilots thereby provide empirical evidence that blockchain-anchored traceability can shorten time-to-isolation of suspect lots and thus reduce public health risk and economic losses from broad, undifferentiated recalls.

In the unfortunate event of a food safety incident or contamination, blockchain facilitates rapid and precise product recalls. Traditional recall processes are often slow, cumbersome, and overly broad due to difficulties in quickly identifying the exact source and distribution of affected products (Jo and Lusk 2023). Blockchain-based traceability systems can drastically reduce the time required to trace a contaminated product back to its origin and track its forward movement through the supply chain.

Pilot projects and implementations in the food industry, such as Walmart's use of IBM Food Trust for tracing mangoes, have demonstrated reductions in traceability time from days or weeks to mere seconds or minutes (Gorman and Walls 2019). For the beef industry, this means that if a particular batch is found to be contaminated, it can be quickly isolated, and only the affected products need to be recalled, rather than issuing a widespread recall that impacts safe products as well. This minimizes public health risks by removing unsafe products from the market faster, reduces economic losses associated with recalls (including product waste and reputational damage), and helps maintain consumer confidence (Gorman and Walls 2019).

Blockchain technology is also a potent tool for combating food fraud. The inherent transparency (within permissioned networks) and immutability of blockchain records make it significantly more difficult for fraudulent actors to perpetrate common types of food fraud in the beef sector. For example, attempts to substitute beef with cheaper meats, misrepresent the country of origin (e.g., passing off imported beef as local premium beef (QUT Design Lab 2023)), falsify expiration dates, or make unsubstantiated claims about quality (e.g., organic, grass-fed) can be more easily detected if the blockchain record shows inconsistencies or lacks verifiable supporting data. The shared nature of the ledger means that any discrepancies or unauthorized changes are visible to relevant stakeholders, acting as a deterrent.

This leads directly to the benefit of ensuring authenticity and provenance. Consumers are increasingly demanding verifiable information about where their food comes from and how it was produced. Blockchain enables the substantiation of claims related to product origin (e.g., "Product of Australia"), breed (e.g., "Angus beef"), animal welfare standards, feeding practices (e.g., "grass-fed," "organic feed"), and other quality attributes. By recording evidence supporting these claims directly on the blockchain (e.g., farm certifications, feed purchase records, veterinary attestations), producers can provide consumers and other stakeholders with a higher degree of assurance, thereby enhancing trust and potentially commanding premium prices for verified products.

Synergistic integration with enabling technologies

The capabilities of blockchain technology in enhancing traceability and food safety in the beef supply chain are significantly amplified when integrated with other advanced Industry 4.0 technologies, particularly the Internet of Things (IoT) for data acquisition and Artificial Intelligence (AI) for data analysis and decision support (Patel et al. 2023).

IoT encompasses a network of physical devices, vehicles, home appliances, and other items embedded with electronics, software, sensors, actuators, and connectivity, enabling these objects to connect and exchange data. In the beef supply chain, IoT sensors play a crucial role in automating the collection of critical data points, thereby improving accuracy, reducing reliance on manual entry—which is prone to errors and manipulation—and providing real-time insights. Various types of sensors are utilized to support these functions. Environmental sensors, such as temperature and humidity sensors, are essential for monitoring the cold chain during transportation and storage of beef products, with data recorded on the blockchain to create an immutable audit trail of temperature compliance (Duan et al. 2024). Gas sensors further support quality assurance by monitoring atmospheric conditions in storage facilities or modified atmosphere packaging, helping to identify spoilage or quality degradation. Location trackers, including GPS sensors, facilitate real-time tracking of livestock during transport and beef shipments, ensuring logistics transparency and verifying routes and delivery times. For livestock health management, wearable biometric sensors, such as smart collars and ear tags, monitor vital signs including body temperature, heart rate, activity levels, and rumination patterns (Conter 2024). This data enables early detection of illness, monitoring of animal welfare, and verification of health status, with key information securely logged on the blockchain. Additionally, identification technologies like RFID tags and NFC chips provide unique identification for animals, carcasses, and product packages, allowing for automated data capture at various checkpoints and seamless recording of transactions on the blockchain. Other specialized sensors may also be integrated depending on specific needs, such as soil moisture and pH sensors for pasture management and feed quality monitoring, or smart tags on veterinary drug packaging to track usage and validity (Yang et al. 2025).

The data flow typically involves sensors collecting data, which is then transmitted wirelessly (e.g., via Bluetooth, LoRaWAN, Wi-Fi, cellular networks) to local gateways or directly to cloud platforms (Khan et al. 2020). From there, relevant data points are formatted and written to the blockchain, often triggered or managed by smart contracts. This automated and objective data capture mechanism significantly enhances the reliability of the information stored on the blockchain, helping to mitigate the "garbage in, garbage out" problem associated with manual data entry. This synergy between IoT and blockchain creates a more trustworthy and real-time digital twin of the physical supply chain.

AI and ML technologies play a pivotal role in enhancing predictive insights and decision support within the beef supply chain. By leveraging the vast volumes of data collected by IoT devices and securely stored on the blockchain, AI/ML algorithms can generate valuable insights to support proactive decision-making. One significant application is predictive analytics for food safety and quality (Shen et al. 2025). AI/ML models, trained on historical and real-time blockchain data such as temperature logs, microbial test results, and sensor readings from animal health monitors, can predict the likelihood of beef spoilage, estimate remaining shelf-life, and identify conditions conducive to pathogen

growth (Agrawal et al. 2025). For example, algorithms analyzing temperature fluctuations recorded on the blockchain can predict their impact on meat quality and safety (Sancheti et al. 2022). Early warnings generated by these models allow stakeholders to implement preemptive interventions, including rerouting shipments, adjusting storage conditions, or prioritizing products for sale, thereby minimizing losses and ensuring product safety.

In addition, AI technologies, particularly those involving computer vision and image analysis, enable automated quality assessment of beef products. Cameras can capture images of carcasses or individual cuts, while ML algorithms objectively analyze visual features such as marbling, color, and fat distribution to assign consistent quality grades (Rizwan Abid et al. 2025). These AI-generated assessments can be directly recorded on the blockchain, providing transparent and verifiable quality information to all supply chain participants. Furthermore, AI algorithms contribute to supply chain optimization and risk management by analyzing blockchain data to improve logistics operations, such as optimizing route planning and inventory management, which helps reduce waste and enhance efficiency (Staci Americas 2024). AI is also instrumental in anomaly detection, identifying patterns that suggest fraudulent activities, compliance breaches, or emerging safety risks. For instance, unusual deviations in transport times, unexpected sensor data variations, or irregular transaction patterns can trigger alerts for further investigation . Additionally, AI supports automated compliance checks by continuously monitoring blockchain records against predefined regulatory or contractual requirements embedded in smart contracts (Issa et al. 2024).

An important practical caveat in IoT–blockchain integration is the energy and resource footprint of the chosen ledger architecture. Public blockchains that implement energy-intensive Proof-of-Work consensus have well-documented environmental impacts and are generally unsuitable for high-frequency IoT anchoring due to both energy cost and per-transaction fee volatility; by contrast, permissioned or Proof-of-Stake (PoS) systems and purpose-built enterprise ledgers (e.g., Hyperledger Fabric, PoA variants) have substantially lower energy demands and are favored in industry pilots (Sedlmeir et al. 2020). Architecture choices therefore affect not only scalability and privacy, but also sustainability: many food-industry pilots employ permissioned ledgers or off-chain data aggregation with on-chain hashes to limit transaction volume and energy cost. The literature and industry reviews recommend energy-aware designs for IoT anchoring (edge aggregation, batching of write operations, use of PoS/PoA or permissioned consensus, and off-chain storage of raw sensor streams with hashed anchors on-chain) to mitigate both energy consumption and device battery constraints while preserving tamper-evident auditability (Bada et al. 2021).

To visually illustrate the synergistic relationship among blockchain, IoT, and AI technologies in the beef supply chain, Fig. 5 has been included. This figure presents a modular framework in which IoT devices play a foundational role in collecting real-time data such as temperature, humidity, GPS locations, and livestock health metrics through various environmental and biometric sensors. This data is wirelessly transmitted to the blockchain platform, where it is securely recorded and managed using smart contracts to automate specific actions and ensure data immutability. The integration of IoT provides the reliable, real-time data feedstock, blockchain provides the secure and immutable platform for recording and sharing this data, and AI provides the intelligence to analyze this data for predictive insights and automated decision-making. This powerful combination can transform the beef supply chain into a more transparent, efficient, resilient, and safe system. The objective, automated data input from IoT sensors acts as a crucial "truth anchor," significantly enhancing the reliability of the information on the blockchain and addressing the GIGO concern. This robust data foundation then allows AI algorithms to generate more accurate and actionable insights, leading to proactive risk management and quality assurance.

Supporting certification and quality assurance schemes

Blockchain technology offers a powerful platform to enhance the credibility, transparency, and efficiency of certification and quality assurance schemes in the beef industry. These schemes, which include certifications for organic production, grass-fed practices, antibiotic-free status, humane animal treatment, and geographical indications like Protected Designation of Origin (PDO) or Protected Geographical Indication (PGI), rely heavily on verifiable proof of compliance with specific standards. Blockchain can revolutionize how this proof is generated, managed, and communicated (Conter 2024).

The digitalization of certification processes is a key application. Instead of relying solely on paper-based certificates or centralized databases, blockchain allows for the creation of digital, immutable records of certifications and the underlying evidence of compliance. For example, to verify a "grass-fed" claim, records of pasture access, feed composition (confirming no grain), and farm management practices can be logged on the blockchain throughout the animal's life (Conter 2024). Similarly, for "antibiotic-free" certification, veterinary records showing no antibiotic treatments, or adherence to strict withdrawal periods if treatment was necessary for animal welfare, can be immutably recorded (Tegeltija et al. 2022). For PDO/PGI products, data verifying geographical origin of animals, specific breeds, traditional production methods, and processing within the designated region can be captured on the blockchain, providing strong evidence to support the claim.

The role of third-party certifiers and auditors can be integrated into blockchain-based systems. These independent bodies can act as trusted nodes or validators within the permissioned blockchain network

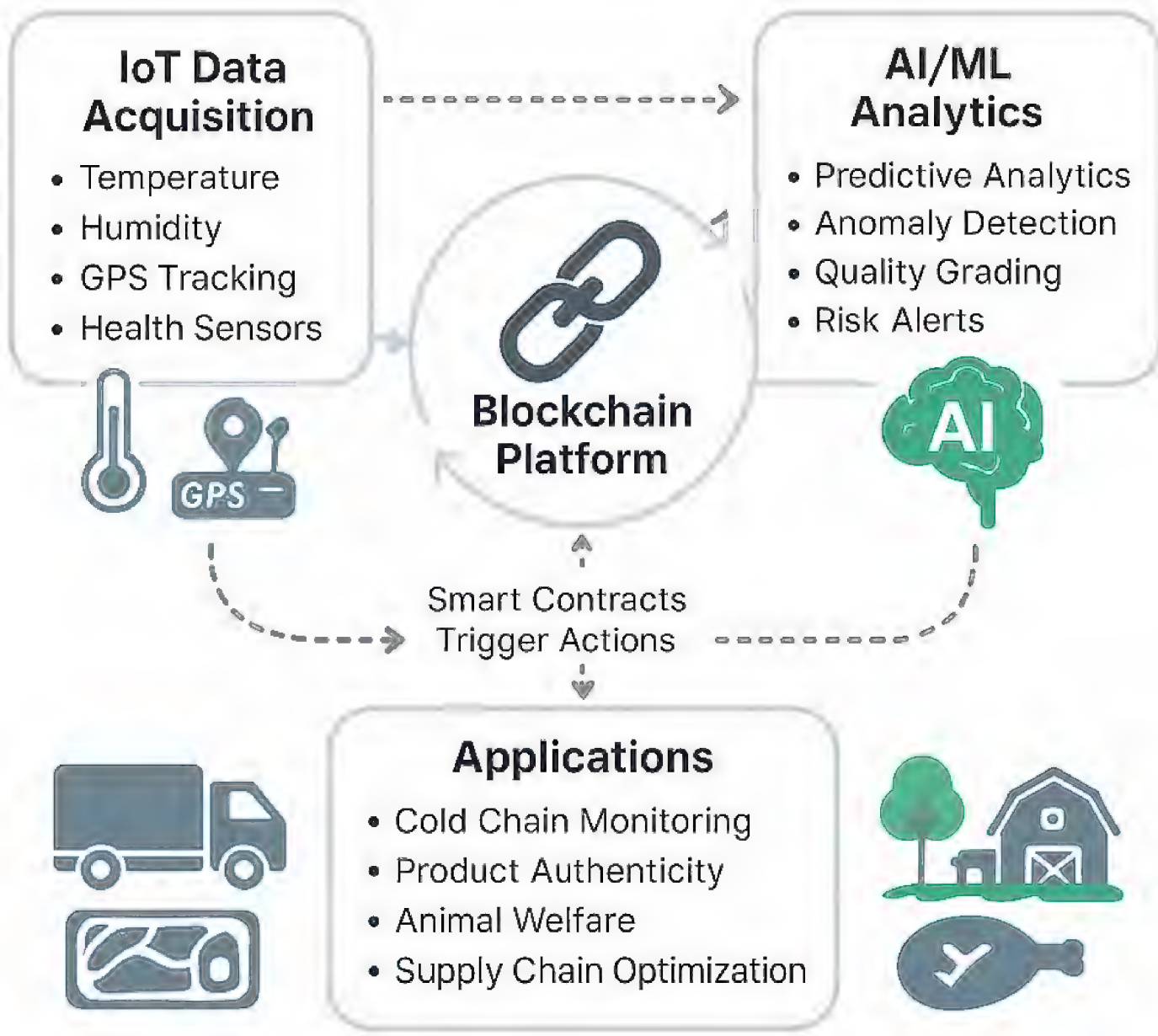

Figure 5. Synergistic integration of blockchain, IoT, and AI/ML technologies in the beef supply chain.

(Conter 2024). Certifiers can review the evidence submitted by producers (which may include IoT sensor data, farm records, and processing logs recorded on the blockchain) and, upon verification of compliance, digitally sign transactions that attest to the certification status. This digital attestation becomes part of the immutable record. Smart contracts could potentially automate certain aspects of the auditing process, for example, by cross-referencing submitted data against predefined standard requirements and flagging anomalies or triggering certification issuance upon successful verification of all criteria (Anon n.d.). This can streamline the certification process, reduce administrative burdens, and potentially lower costs for both producers and certifiers (Rabhi 2024).

Blockchain significantly enhances the integrity of claims associated with these certifications. The immutability and transparency of the blockchain make it extremely difficult to falsify certification documents or make fraudulent claims about production standards. If a producer claims their beef is organic, the blockchain should contain verifiable records from accredited certifiers and evidence of compliant farming practices throughout the production cycle. This increases the credibility of legitimate certifications and helps protect the value of premium brands, such as those with PDO or PGI status, which are often targets for counterfeiting. Consumers, retailers, and regulatory authorities can have greater confidence that the claims made on product labels are backed by verifiable, tamper-proof data.

The technology facilitates the creation of secure, time-stamped, and unalterable digital audit trails for all activities related to certification and quality assurance (Iftekhar and Cui 2021). Every inspection, verification step, data submission, and certification issuance can be recorded as a transaction on the blockchain. Authorized parties, including certifiers, regulators, and potentially consumers (through controlled access mechanisms like QR codes), can access these audit trails to verify compliance history and the validity of certifications. This level of transparency and auditability strengthens the entire quality assurance ecosystem. For instance, the SAFE platform described by (Tegeltija et al. 2022) aims to harmonize data with organic legislation, use blockchain for data consistency and history, and involve certified professionals for validating manually entered data, thereby enabling traceability of the organic certification process itself.

Comparative analysis of blockchain platforms for beef supply chains

The selection of an appropriate blockchain platform is a critical decision for any organization looking to implement blockchain-based traceability in the beef supply chain. Different platforms offer varying features, capabilities, and trade-offs, and the optimal choice depends heavily on the specific requirements of the intended application. Key evaluation criteria for comparing these platforms include: scalability, which refers to the platform's ability to

handle a large volume of transactions and data efficiently (often measured in transactions per second or TPS) and its capacity for data storage ; smart contract functionality, including the sophistication of the smart contracts supported and the programming languages available for their development (Anglen 2023); the consensus mechanism employed, which impacts security, speed, energy consumption, and decentralization (Anyibama et al. 2025); the permissioning model (public, private, or consortium), which dictates access control and governance (Joo and Han 2021); data privacy features, such as support for confidential transactions or integration with privacy-enhancing technologies; interoperability with existing enterprise systems and other blockchain networks; ease of development and maintenance, influenced by available tools, documentation, and cossssmmunity support; and overall cost, including setup, transaction fees (if any), and ongoing operational expenses (Jafi et al. 2023).

Several blockchain platforms have been utilized or considered for food supply chain applications:

Hyperledger Fabric: This is a permissioned blockchain framework hosted by the Linux Foundation, specifically designed for enterprise solutions. It is often favored for supply chain applications due to its modular architecture, which allows for pluggable components like consensus mechanisms (e.g., Raft, as used in some food safety pilots (Oh et al. 2025)) and membership services (Ferdousi et al. 2020). Hyperledger Fabric supports smart contracts (called "chaincode") written in general-purpose programming languages like Go, Java, and Node.js. Its permissioned nature allows for control over participant identities and data access, which is crucial for business confidentiality. Studies suggest it offers good scalability for enterprise needs, with some reporting high TPS rates. It is considered a strong candidate for beef traceability systems due to these features.

Ethereum: Ethereum is a well-known public blockchain platform that pioneered sophisticated smart contract capabilities using its native Solidity programming language (Manne and Makineni 2023). While the public Ethereum network faces challenges with scalability (historically low TPS and high transaction "gas" fees) and the energy consumption of its former PoW consensus mechanism (it has since transitioned to PoS, which is more efficient (Kumar et al. 2025)), private or consortium instances of Ethereum can be deployed. Furthermore, Layer 2 scaling solutions are being developed to improve its throughput. Its robust smart contract ecosystem and large developer community are advantages, but for high-volume, low-cost transactions typical of a beef supply chain, the public network may be less suitable without significant scaling solutions or private deployment (Jafi et al. 2023).

VeChain (VeChainThor): This is a public blockchain platform specifically designed with a focus on supply chain management and integrating with IoT devices (Colomberotto 2020). It uses a Proof of Authority (PoA) consensus mechanism, which aims to provide a balance of performance and decentralization. VeChain offers tools and protocols to facilitate the tracking of goods and the verification of authenticity. Its specific features tailored for supply chain use cases make it a relevant platform for consideration in the food sector.

IBM Food Trust: This is not a foundational blockchain platform itself, but rather a commercial solution built on Hyperledger Fabric. It has gained significant traction with major global retailers (e.g., Walmart, Carrefour) and food producers. IBM Food Trust provides a permissioned network where participants can share food system data. Its architecture is designed to enable traceability, enhance food safety, and improve supply chain efficiency. As a solution layer, it offers pre-built modules and services tailored to the food industry, potentially reducing development time and complexity for adopting companies.

Other platforms like Hyperledger Sawtooth, EOS. IO, and Hyperledger Iroha have also been evaluated for food supply chain applications, each with its own set of strengths and weaknesses regarding the criteria mentioned above (Jafi et al. 2023). For example, Hyperledger Sawtooth offers flexibility with pluggable consensus (including Proof of Elapsed Time - PoET) and support for various transaction processors, while EOS.IO aims for high TPS using Delegated Proof of Stake (DPoS).

The ultimate choice of a blockchain platform for a beef supply chain will involve a careful assessment of these factors against the specific operational needs, business objectives, and technical capabilities of the implementing organizations. For instance, a large-scale international beef exporter with many partners might prioritize a highly scalable, permissioned platform with robust data governance features like Hyperledger Fabric or a solution like IBM Food Trust. A smaller, local cooperative might explore simpler, perhaps more cost-effective, private blockchain solutions. The dynamic nature of blockchain technology also means that platforms are continuously evolving, with new features and scaling solutions emerging regularly. A comparison of these platforms is presented in Table 2.

Illuminating the path: Case studies and pilot projects in the beef sector

The theoretical benefits of blockchain technology for the beef supply chain are compelling, but its practical viability and impact are best understood through an examination of real-world implementations and pilot projects. Several initiatives globally have explored the use of blockchain to address specific challenges in beef traceability and food safety.

BeefLedger (Australia) provides one of the clearest examples where consumer valuation was empirically measured. The QUT/UQ evaluation of BeefLedger-credentialed Australian beef found that a large majority of attendees and surveyed consumers reported willingness to pay extra for blockchain-credentialed Australian cuts: 78.6% of local control respondents and 92.9% of foreign control respondents stated they would pay a premium, with mean

Table 2. Comparative analysis of selected blockchain platforms for beef supply chain applications.

Feature	Hyperledger Fabric	Ethereum (Public/Permissioned)	VeChain (VeChainThor)	IBM Food Trust (on Hyperledger Fabric)
Type	Permissioned (Consortium/ Private)	Public (default), can be Private/ Consortium	Public, with governance features aimed at enterprise use	Permissioned (Consortium) **(J. Anyibama et al. 2025)**
Consensus Mechanism	Pluggable (e.g., Raft, PBFT)	PoS (formerly PoW) for public; various for permissioned	Proof of Authority (PoA)	Based on Hyperledger Fabric (e.g., Raft)
Smart Contracts	"Chaincode" (Go, Java, Node.js)	Solidity, Vyper (robust ecosystem)	Solidity compatible, built-in templates	Hyperledger Fabric chaincode
Scalability (TPS)	High (e.g., up to 20,000 TPS reported in some studies)	Low on public mainnet (e.g., ~15–30 TPS); higher with Layer 2s or private instances	Moderate to High (designed for enterprise volume)	Dependent on underlying Fabric configuration, designed for enterprise scale
Data Privacy	Channels for private transactions, granular access control	Limited on public mainnet; better in private/consortium setups; ZKPs emerging	Controllable data access through smart contracts	Permissioned access, data ownership controls
Interoperability	Developing, focus on enterprise integration	Developing (cross-chain solutions, standards like ERCs)	Focus on IoT integration, tools for cross-chain interaction	Aims for industry-wide participation, uses GS1 standards
Suitability for Beef SC	High, due to permissioning, scalability, and enterprise focus	Moderate; public network costly/ slow, private viable but less ecosystem than Fabric for SC	High, due to supply chain focus and IoT integration	High, as a tailored food industry solution
Key Considerations	Complexity of setup, governance model critical	Gas fees and congestion (public), maturity of Layer 2s	Adoption rate, ecosystem development	Vendor lock-in, subscription costs
Adoption in Food Industry so far	High — multiple enterprise pilots and commercial deployments (IBM Food Trust / Hyperledger Fabric). Notable: Walmart–IBM Food Trust mango & pork pilots (Food Trust), Carrefour and other retailers; widely used in enterprise food traceability pilots.	Limited on public mainnet for high-volume per-item writes (fee and latency issues); private/consortium or Layer-2 deployments explored in pilots but less common in mainstream adoption than permissioned ledgers for food traceability.	Moderate–High in selected markets — large pilots and rollouts in China (Walmart China Blockchain Traceability Platform / Walmart China + VeChain + PwC) and commercialised QR-based traceability for multiple product lines in China.	Same as Hyperledger Fabric
Illustrative References	**(Ferdousi et al. 2020)**	**(Manne and Makineni 2023)**	**(Colomberotto 2020)**	**(Adesiyan 2025)**

stated WTP for the control groups of ~123.0 CNY (local) and ~127.9 CNY (foreign) (QUT Design Lab et al. 2020). Beyond Australia–China trade, retailers have reported trust-linked commercial signals, for example Carrefour's early blockchain programs in Europe that coincided with sales uplift on traceable lines, and JD.com/Kerchin's QR-code beef traceability in China designed to expose farm-to-plate histories at the consumer interface (Pavithra et al. 2025). The study also reports mean extra-amounts (willingness to pay extra) in subgroup analyses (for example, local treatment respondents' mean extra amount ≈ 44.7 CNY). These results indicate a measurable commercial value to provenance credentials in the Chinese market, while also demonstrating sensitivity to how the credential is presented to consumers (video treatments in the experiment affected WTP levels). At the operational level, BeefLedger adopted a permissioned blockchain and a multisignature validation approach to record animal IDs, farm data, processing steps and logistics while flagging the persistent "garbage in, garbage out" (GIGO) risk and the need for off-chain data validation and stakeholder alignment. These findings suggest that traceability credentials can command a consumer premium (and thus a potential ROI pathway), but that conversion to real sales depends on consumer communication and robust on-farm and processing data verification. Challenges included ensuring the accuracy of initial data input (the GIGO problem (Zhang et al. 2023)) and fostering collaboration among diverse stakeholders. Lessons learned emphasized the need for robust data validation mechanisms beyond the blockchain itself and the importance of aligning technological solutions with existing business processes and stakeholder incentives (Cao et al. 2022). The project also highlighted the strategic need to digitally transform supply chain governance to improve transparency and response times.

JBS's Transparent Livestock Farming Platform (developed with Ecotrace) represents a large-scale, governance-oriented deployment that seeks to extend traceability and socio-environmental compliance beyond direct suppliers by enabling suppliers to register their own upstream suppliers (Zanetoni et al. 2024). The platform has been publicly described by JBS as a means to map supplier networks and improve zero-deforestation monitoring and compliance support programs (e.g., "Green Offices") (Steve 2021). However, independent reporting and implementation audits indicate important adoption constraints: indirect suppliers—particularly small and remote ranchers—have expressed reluctance to register or share detailed data because of concerns about data privacy, land-title ambiguity, the costs and administrative burden of registration, and potential reputational/legal exposure when historical land-use issues exist. Investigative journalism and NGO reports additionally note that, although JBS reports substantial progress (company statements cite high proportions of registered purchases), mapping and verification of the entire indirect supplier base remain incomplete and supplier sign-up is an ongoing objective. These realities expose a practical limitation of platform deployments: technical system availability alone does not guarantee full coverage, and targeted capacity building, incentives and privacy-preserving architectures are necessary complements.

JD.com and Kerchin. JD.com publicly announced a blockchain pilot with Kerchin (Inner Mongolia) to anchor farm-to-package information behind QR codes so consumers could view origin, feed and logistics details when purchasing beef (announced in 2018). The project illustrates large e-commerce players' potential to scale traceability interfaces to consumers. However, public documentation of this initiative contains descriptive rollout information rather than standardized quantitative outcome metrics (for example, JD's press coverage and contemporary reporting describe traceability features and deployment scale but do not report peer-reviewed measurements such as percentage reductions in recall time or quantified increases in consumer trust). Therefore, while JD.com demonstrates practical deployment at retail scale, robust, comparable outcome metrics have not been widely published for this pilot in the academic record.

Tyson Foods. Tyson has selected supplier-visibility platforms (e.g., FoodLogiQ Connect) and participated in traceability pilots with industry platforms (and in some collaborative pilots with IBM Food Trust partners). Company and vendor announcements emphasise improved supplier data visibility and streamlined incident reporting, but detailed numeric performance indicators for meat/beef pilots (for example, % reduction in average trace-back time specifically for beef lots, or measured % increase in consumer trust) are mostly reported in proprietary, vendor-facing documentation or press statements rather than peer-reviewed literature. By contrast, publicly available IBM Food Trust deployments (e.g., retailer pilots) show large reductions in trace-back times (classic IBM/Walmart example: days → seconds), and recent empirical analyses report significantly shorter recall responsiveness where blockchain systems have been implemented. Thus, for Tyson and similar large processors, the literature supports the potential for large recall-time and responsiveness gains, but quantifying those gains for specific corporate pilots requires access to company data or independent evaluations.

The IBM Food Trust platform, built on Hyperledger Fabric, represents a significant multi-stakeholder initiative involving major retailers like Walmart and Carrefour, and numerous food producers. While not exclusively focused on beef, its applications in tracking pork in China by Walmart and other food items demonstrate key capabilities relevant to the beef sector. The platform allows permissioned participants to upload and access data about food products as they move through the supply chain. A widely cited outcome is the dramatic reduction in time taken to trace the origin of a food item – for example, from several days to just 2.2 seconds for mangoes in a Walmart pilot (Gorman and Walls 2019). This capability is directly transferable to the beef supply chain for rapid recall management and contamination source identification. The platform emphasizes data ownership by the participant who uploads it, with control over who can access that data. Challenges include onboarding a diverse range of suppliers, especially smaller ones, and ensuring consistent data quality.

Conclusions and future perspectives

Blockchain is best understood as a trust and auditability architecture for beef supply chains—not a panacea. Its net benefits emerge only when technical choices are aligned with sector standards, governance, and incentives, and when participation is feasible for all actors, including smallholders. At present, production-grade deployments still face throughput and latency constraints at national scale; the absence of widely adopted data models across platforms elevates integration costs; and the value proposition remains uneven across actor types. These frictions are magnified in low- and middle-income country (LMIC) contexts, where structural barriers—rural connectivity gaps, smartphone affordability, and limited digital skills—raise onboarding and recurrent data-capture costs for producers and traders. Recent GSMA assessments indicate a persistent global "usage gap," with roughly 38–39% of the world's population living under mobile broadband coverage but not using it, while about 4% remain uncovered; those excluded are disproportionately rural residents in LMICs, women, and lower-income groups, underscoring why purely digital traceability solutions can stall without complementary inclusion measures.

Strengthening human and institutional capabilities is therefore as important as maturing the technology stack. Systematic reviews of agricultural digitalisation consistently identify limited digital literacy and training opportunities among smallholders as primary adoption bottlenecks; targeted extension services and hands-on training correlate with higher uptake and more effective use of digital tools. For blockchain-enabled traceability, this implies co-designing onboarding workflows that minimise manual data entry, providing vernacular interfaces, and coupling deployments with basic digital skills programs delivered through extension networks and producer organisations.

Looking ahead, four intertwined priorities can accelerate impact. First, scalability and efficiency should be pursued through fit-for-purpose consensus and batching in permissioned networks, alongside pragmatic performance engineering at the application and data layers. Second, interoperability requires sector-specific reference profiles grounded in global standards—most notably GS1 EPCIS/CBV, now at version 2.0, which provides a web- and IoT-ready event data model and APIs for cross-enterprise visibility. Third, privacy-by-design should move from aspiration to implementation via selective disclosure and secure computation that reconcile legitimate confidentiality with regulatory and market demands for transparency. Fourth, equitable value distribution must be assessed with metrics that capture who gains or loses across the chain, with explicit attention to the costs borne by smallholders and micro-enterprises in LMIC settings.

Enabling public policy can materially reduce first-mover and coordination risks. Practical instruments include cost-share grants for data-capture hardware (e.g., eID tags, readers), support for digital extension and training, and co-investment in rural connectivity and registries. Recent examples illustrate feasibility: Australia's national agricultural

traceability grants have provided targeted funding to improve and expand traceability systems across animal sectors, while additional sector-specific grants and policy signals have supported electronic identification for ruminants to strengthen biosecurity and market access. India's National Digital Livestock Mission ("Bharat Pashudhan") aims to create digital public infrastructure for animal identity and services, which can interoperate with supply-chain solutions. These initiatives point to a realistic policy toolkit that can de-risk adoption for producers and processors while advancing national objectives in biosecurity, trade, and consumer trust.

On complementary technologies, near-term gains will come from grounded integrations rather than speculation. Edge-AI in tags, readers, and gateways can support on-animal analytics and anomaly detection, while digital-twin approaches that fuse on-chain events with IoT time-series can enable predictive quality assurance and targeted recalls. Token-based incentives remain promising but should be treated as exploratory until supported by robust, replicated evidence. Early pilots—such as BeefLedger's provenance experiments and associated studies reporting consumer willingness to pay premiums for blockchain-credentialed Australian beef—suggest market pull, yet large-scale effectiveness and persistence of such incentives remain to be demonstrated in diverse geographies and channels.

We therefore conclude with a practical call to action. The beef sector should establish a global, multi-stakeholder traceability consortium that convenes industry platforms, producer groups, and regulators together with standards bodies and sustainability fora. The consortium's initial mandate would be to: (i) adopt a reference implementation profile for beef grounded in GS1 EPCIS 2.0/CBV (covering core event types, master data, and conformance tests); (ii) align with the World Organisation for Animal Health (WOAH) Terrestrial Code principles on animal identification and traceability; (iii) publish open onboarding toolkits (templates, test data, validation services) tailored for smallholders and micro-enterprises; and (iv) coordinate governance and change-management processes across regions. Interoperability precedents already exist: the seafood sector's Global Dialogue on Seafood Traceability (GDST) provides a living example of a cross-industry, EPCIS-based profile and implementation guidance designed to enable event-based data exchange while respecting data sensitivity. Beef stakeholders—including those active in the Global Roundtable for Sustainable Beef (GRSB) and allied national roundtables—are well placed to anchor such a consortium, accelerate harmonisation, and lower integration costs through shared specifications and governance.

In sum, realising the promise of blockchain for safer, more transparent beef depends on meeting users where they are: solving everyday data-capture pain points in abattoirs and on farms; funding the last-mile infrastructure and skills that LMIC actors need to participate; and converging, at pace, on interoperable, privacy-respecting data standards. With coordinated investment in technology, policy, and people—and with a standards-anchored consortium to steward interoperability—the sector can move beyond pilots toward durable, system-level improvements in traceability and food safety.

Author contributions

J.T designed the research study, performed the research, and wrote the manuscript.

Data collection and analysis

Data sharing is not applicable as no data were generated or analyzed.

Acknowledgments

I gratefully acknowledge the assistance and instruction from professor Shaohe Liu of Guangdong University of Finance & Economics, in China.

References

Bada AO, Damianou A, Angelopoulos CM, Katos V (2021) Towards a green blockchain: A review of consensus mechanisms and their energy consumption. In: 2021 17th International Conference on Distributed Computing in Sensor Systems (DCOSS), 503–511. https://doi.org/10.1109/DCOSS52077.2021.00083

Adesiyan KT (2025) Blockchain technology: a game changer for food traceability and security. IOSR Journal of Business and Management (IOSR-JBM) 27: 1–8. https://doi.org/10.9790/487X-2701050108

Adjei VY, Mensah GI, Parry-Hanson Kunadu A, Tano-Debrah K, Ayi I, Addo KK (2022) Microbial Safety of Beef Along Beef Value Chains in the Ashaiman Municipality of Ghana. Frontiers in Veterinary Science 9: 813422. https://doi.org/10.3389/fvets.2022.813422

Afzaal M, Saeed F, Hussain M, Shahid F, Siddeeg A, Al-Farga A (2022) Proteomics as a promising biomarker in food authentication, quality and safety: A review. Food Science & Nutrition 10: 2333–2346. https://doi.org/10.1002/fsn3.2842

Agrawal K, Goktas P, Holtkemper M, Beecks C, Kumar N (2025) AI-driven transformation in food manufacturing: a pathway to sustainable efficiency and quality assurance. Frontiers in Nutrition 12: 1553942. https://doi.org/10.3389/fnut.2025.1553942

Akkerman F, Lalla-Ruiz E, Mes M, Spitters T (2022) Cross-Docking: Current Research Versus Industry Practice and Industry 4.0 Adoption. In: Bondarouk T, Olivas-Luján MR (Eds) Advanced Series in Management. Emerald Publishing Limited, 69–104. https://doi.org/10.1108/S1877-636120220000028007

Alharbi SH, Alzahrani AM, Syed TA, Alqahtany SS (2024) Integrity and Privacy Assurance Framework for Remote Healthcare Monitoring Based on IoT. Computers 13: 164. https://doi.org/10.3390/computers13070164

Anglen J (2023) Introduction to blockchain architecture design. 5 key considerations in blockchain architecture design. https://www.rapidinnovation.io/post/5-key-considerations-in-blockchain-architecture-design [May 13, 2025]

Anyibama BJ, Orjinta KK, Onotole EF, Olalemi AA, Olayinka OT, Ogunwale GE, Fadipe EO, Daniels EO (2025) Blockchain application in food supply chains: A critical review and agenda for future studies. International Journal of Innovative Science and Research Technology, 2345–2352. https://doi.org/10.38124/ijisrt/25feb1659

Anon (n.d.) Blockchain Verification for Organic Produce? → Scenario. Prism → Sustainability Directory. https://prism.sustainability-directory.com/scenario/blockchain-verification-for-organic-produce/ [May 13, 2025]

Authority EFS, European Centre for Disease Prevention and Control (2025) The European Union summary report on antimicrobial resistance in zoonotic and indicator bacteria from humans, animals and food in 2022–2023. EFSA Journal 23: e9237. https://doi.org/10.2903/j.efsa.2025.9237

Awad M, Ndiaye M, Osman A (2021) Vehicle routing in cold food supply chain logistics: a literature review. The International Journal of Logistics Management 32: 592–617. https://doi.org/10.1108/IJLM-02-2020-0092

Borders SE, Schwartz TE, Mayer TR, Gehring KB, Griffin DB, Kerth CR, Belk KE, Edwards-Callaway L, Scanga JA, Nair MN, Morgan JB, Douglas JB, Pfeiffer MM, Mafi GG, Harr KM, Lawrence TE, Tennant TC, Lucherk LW, O'Quinn TG, Beyer ES, Bass PD, Garcia LG, Bohrer BM, Pempek JA, Garmyn AJ, Maddock RJ, Carr CC, Pringle TD, Scheffler TL, Scheffler JM, Stelzleni AM, Gonzalez JM, Underwood KR, Harsh BN, Waters CM, Savell JW (2024) National Beef Quality Audit—2022: Transportation, mobility, live cattle, and hide assessments to determine producer-related defects that affect animal welfare and the value of market cows and bulls at processing facilities. Translational Animal Science 8: txae033. https://doi.org/10.1093/tas/txae033

Broom DM (2021) Broom and Fraser's domestic animal behaviour and welfare. 6th edn. CABI, UK. https://doi.org/10.1079/9781789249835.0000

Cao S, Foth M, Powell W, Miller T, Li M (2022) A blockchain-based multisignature approach for supply chain governance: A use case from the Australian beef industry. Blockchain: Research and Applications 3: 100091. https://doi.org/10.1016/j.bcra.2022.100091

Castanon CP, Hernandez D, Khetrapal AN, Hellberg RS (2025) Comparison of PCR-based methods for the detection of canned tuna species. Journal of Food Science 90: e70424. https://doi.org/10.1111/1750-3841.70424

Caveen A, Archer M, Platt M (2021) The impact of improved traceability on the safety of food. RS Standards Limited / RS Standards Limited, Forsyth House, Cromac Square, Belfast, BT2 8LA, Northern Ireland, United Kingdom. Technical Report. https://thegdst.org/wp-content/uploads/2024/01/impact_of_improved_traceability_on_the_safety_of_food___full_report.pdf

Chatellier V (2021) Review: International trade in animal products and the place of the European Union: main trends over the last 20 years. Animal 15: 100289. https://doi.org/10.1016/j.animal.2021.100289

Chen Q, Qian J, Yang H, Wu W (2022) Sustainable food cold chain logistics: From microenvironmental monitoring to global impact. Comprehensive Reviews in Food Science and Food Safety 21: 4189–4209. https://doi.org/10.1111/1541-4337.13014

Cil AY, Abdurahman D, Cil I (2022) Internet of Things enabled real time cold chain monitoring in a container port. Journal of Shipping and Trade 7: 9. https://doi.org/10.1186/s41072-022-00110-z

Cohen T (2022) The next pandemic: A pragmatic and ethical discussion about the looming threat of antibiotic resistance. Voices in Bioethics 8: 1–11. https://doi.org/10.52214/vib.v8i.9509

Colomberotto A (2020) Blockchain technology in meat supply chain: Economic and operational implications. Master thesis. Ca' Foscari University of Venice.

Conter M (2024) Recent advancements in meat traceability, authenticity verification, and voluntary certification systems. Italian Journal of Food Safety 14: 12971. https://doi.org/10.4081/ijfs.2024.12971

Duan K, Onyeaka H, Pang G (2024) Leveraging blockchain to tackle food fraud: Innovations and obstacles. Journal of Agriculture and Food Research 18: 101429. https://doi.org/10.1016/j.jafr.2024.101429

EIT Food (2023) Case study: The beef supply chain. https://www.futurelearn.com/info/courses/understanding-food-supply-chains/0/steps/74765 [May 13, 2025]

El Khatib M, Alzoubi HM, Hamidi S, Alshurideh M, Baydoun A, Al-Nakeeb A (2023) Impact of using the internet of medical things on e-healthcare performance: Blockchain assist in improving smart contract. ClinicoEconomics and Outcomes Research Volume 15: 397–411. https://doi.org/10.2147/CEOR.S407778

Endoh EKM, Pandey J, Sajow AA (2021) Analysis of the supply chain of local beef cattle commodity and beef in north sulawesi. International Journal of Applied Business and International Management 6: 78–85. https://doi.org/10.32535/ijabim.v6i3.1331

Farokhnia S, Kafshdar Goharshady A (2023) Alleviating High Gas Costs by Secure and Trustless Off-chain Execution of Smart Contracts. In: Proceedings of the 38th ACM/SIGAPP Symposium on Applied Computing. ACM, Tallinn Estonia, 258–261. https://doi.org/10.1145/3555776.3577833

Ferdousi T, Gruenbacher D, Scoglio CM (2020) A permissioned distributed ledger for the US beef cattle supply chain. IEEE Access 8: 154833–154847. https://doi.org/10.1109/ACCESS.2020.3019000

Fu L, Zhou Q, Jin M, Wu W (2025) Large language models as spectrographic assistants: Opportunities and challenges in laboratory data analysis. Environmental Chemistry and Safety 1: 9600002. https://doi.org/10.26599/ECS.2025.9600002

Gadge SS, Narayan KD, Lahu PR, Uttam SV (2024) A review on traceability system for fruit and vegetables agricultural products using blockchain. International Journal of Advanced Research in Science, Communication and Technology, 15–20. https://doi.org/10.48175/IJARSCT-22003

Gaynutdinov I, Mukhametgaliev F, Avhadiev F (2021) The state and features of the development of livestock industries in russia and abroad. Vestnik of Kazan State Agrarian University 16: 86–95. https://doi.org/10.12737/2073-0462-2021-86-95

Gokul Prasad C, Vipshal WG, Leon O, Thamarai Kannan A, Sabarinathan B, Arun Vignesh N (2023) Relating DT Framework in IOT based Heart Rate and Blood Oxygen Monitor with Automatic Data Saving. In: 2023 International Conference on Computer Communication and Informatics (ICCCI). IEEE, Coimbatore, India, 1–4. https://doi.org/10.1109/ICCCI56745.2023.10128596

Gorman D, Walls S (2019) Food safety: How blockchain mitigates losses during U.S. meat recalls. https://www.american.edu/kogod/news/blockchain-food-safety.cfm [May 13, 2025]

Havelaar AH, Sapp AC, Amaya MP, Nane GF, Morgan KM, Devleesschauwer B, Grace D, Knight-Jones T, Kowalcyk BB (2022) Burden of foodborne disease due to bacterial hazards associated with beef, dairy, poultry meat, and vegetables in Ethiopia and Burkina Faso, 2017. Frontiers in Sustainable Food Systems 6: 1024560. https://doi.org/10.3389/fsufs.2022.1024560

Hewa T, Ylianttila M, Liyanage M (2021) Survey on blockchain based smart contracts: Applications, opportunities and challenges. Journal of Network and Computer Applications 177: 102857. https://doi.org/10.1016/j.jnca.2020.102857

Hidayati J, Vamelia R, Hammami J, Endri E (2023) Transparent distribution system design of halal beef supply chain. Uncertain Supply Chain Management 11: 31–40. https://doi.org/10.5267/j.uscm.2022.12.003

Iftekhar A, Cui X (2021) Blockchain-based traceability system that ensures food safety measures to protect consumer safety and COVID-19 free supply chains. Foods 10: 1289. https://doi.org/10.3390/foods10061289

Igwe AN, Ewim CP-M, Ofodile OC, Sam-Bulya NJ (2024) Leveraging blockchain for sustainable supply chain management: A data privacy and security perspective. International Journal of Frontline Research and Reviews 3: 61–75. https://doi.org/10.56355/ijfrr.2024.3.1.0030

Issa A, Mekanna AN, Doumit J, Bou-Mitri C (2024) Redefining food safety: the confluence of Web 3.0 and AI technologies in the meat supply chain—a systematic review. International Journal of Food Science and Technology 59: e1–e14. https://doi.org/10.1111/ijfs.17168

Jafi A, Andersen B, Yuen Y, Antony Y (2023) Evaluation of Blockchain Platforms for Food Supply Chain System. https://doi.org/10.13140/RG.2.2.34282.49608

Jamil F, Iqbal N, Imran, Ahmad S, Kim D (2021) Peer-to-Peer Energy Trading Mechanism Based on Blockchain and Machine Learning for Sustainable Electrical Power Supply in Smart Grid. IEEE Access 9: 39193–39217. https://doi.org/10.1109/ACCESS.2021.3060457

Tarawneh H, Obeidat H, Sawalha B (2024) Application of Hazard Analysis Critical Control Point (HACCP) principles to beef mortadella production. African Journal of Food, Agriculture, Nutrition and Development 24: 24337–24363. https://doi.org/10.18697/ajfand.133.24890

Jo J, Lusk JL (2023) The intrinsic and instrumental values of blockchain to provide beef traceability in Hong Kong, South Korea, and the United States. Foods 12: 4209. https://doi.org/10.3390/foods12234209

Joo J, Han Y (2021) An evidence of distributed trust in blockchain-based sustainable food supply chain. Sustainability 13: 10980. https://doi.org/10.3390/su131910980

Kamath R (2018) Food traceability on blockchain: Walmart's pork and mango pilots with IBM. The Journal of the British Blockchain Association 1: 47–53. https://doi.org/10.31585/jbba-1-1-(10)2018

Kaur A, Singh G, Kukreja V, Sharma S, Singh S, Yoon B (2022) Adaptation of IoT with Blockchain in Food Supply Chain Management: An Analysis-Based Review in Development, Benefits and Potential Applications. Sensors 22: 8174. https://doi.org/10.3390/s22218174

Kaushal RK, Kumar N, Panda SN, Kukreja V (2021) Immutable smart contracts on blockchain technology: Its Benefits and Barriers. In: 2021 9th International Conference on Reliability, Infocom Technologies and Optimization (trends and Future Directions) (ICRITO). IEEE, Noida, India, 1–5. https://doi.org/10.1109/ICRITO51393.2021.9596538

Khan MdA, Hossain MdE, Islam MdS, Rahman MS, Sudhakaran PO, Dey MM (2023) A systematic review of fish adulteration and contamination in Bangladesh: A way forward to food safety. Reviews in Aquaculture 15: 1574–1589. https://doi.org/10.1111/raq.12801

Khan PW, Byun Y-C, Park N (2020) IoT-blockchain enabled optimized provenance system for food industry 4.0 using advanced deep learning. Sensors 20: 2990. https://doi.org/10.3390/s20102990

Khan SN, Loukil F, Ghedira-Guegan C, Benkhelifa E, Bani-Hani A (2021) Blockchain smart contracts: Applications, challenges, and future trends. Peer-to-Peer Networking and Applications 14: 2901–2925. https://doi.org/10.1007/s12083-021-01127-0

Khanna A, Jain S, Burgio A, Bolshev V, Panchenko V (2022) Blockchain-Enabled Supply Chain platform for Indian Dairy Industry: Safety and Traceability. Foods 11: 2716. https://doi.org/10.3390/foods11172716

Kumar A, Kaur C, Kumar A, Akhil (2025) Blockchain beyond cryptocurrencies: a technological evolution across industries. International Journal of Research Publication and Reviews 6: 16902–16909.

Lafargue P, Rogerson M, Parry GC, Allainguillaume J (2022) Broken chocolate: biomarkers as a method for delivering cocoa supply chain visibility. Supply Chain Management: an International Journal 27: 728–741. https://doi.org/10.1108/SCM-11-2020-0583

Lhermie G, Sauvage P, Tauer LW, Chiu LV, Kanyiamattam K, Ferchiou A, Raboisson D, Scott HM, Smith DR, Grohn YT (2020) Economic effects of policy options restricting antimicrobial use for high risk cattle placed in U.S. feedlots. Loor JJ (Ed.). PLoS ONE 15: e0239135. https://doi.org/10.1371/journal.pone.0239135

Liu K, Xing R, Sun R, Ge Y, Chen Y (2023) An accurate and rapid way for identifying food geographical origin and authenticity: Editable DNA-traceable barcode. Foods 12: 17. https://doi.org/10.3390/foods12010017

Lucas A, Geneiatakis D, Soupionis Y, Nai-Fovino I, Kotsakis E (2021) Blockchain technology applied to energy demand response service tracking and data sharing. Energies 14: 1881. https://doi.org/10.3390/en14071881

Ma D, Li K, Qin H, Hu J (2024) Impacts of blockchain technology on food supply chains with potential food contamination. Electronic Commerce Research and Applications 64: 101375. https://doi.org/10.1016/j.elerap.2024.101375

Manne MV, Makineni M (2023) Improving the supply chain management in indian agriculture secured with blockchain. Bachelor's thesis. Sathyabama Institute of Science and Technology.

McLachlan T (2022) From the Chief Executive and IFST News. Food Science and Technology 36: 8–17. https://doi.org/10.1002/fsat.3604_3.x

McQueenie J, Foth M, Hearn G (2024) BeefLegends: Connecting Food Producers and Consumers Across Borders. In: McQueenie J, Foth M, Hearn G (Eds) Community, Culture, Commerce: The Intermediary in Design and Creative Industries. Springer Nature, Singapore, 47–80. https://doi.org/10.1007/978-981-99-7889-2_4

Modi B, Timilsina H, Bhandari S, Achhami A, Pakka S, Shrestha P, Kandel D, Gc DB, Khatri S, Chhetri PM, Parajuli N (2021) Current Trends of Food Analysis, Safety, and Packaging. Al-Alawi A (Ed.) International Journal of Food Science 2021: 1–20. https://doi.org/10.1155/2021/9924667

Moreira LC, Rosa GJM, Schaefer DM (2021) Beef production from cull dairy cows: a review from culling to consumption. Journal of Animal Science 99: skab192. https://doi.org/10.1093/jas/skab192

Nehal N, Choudhary B, Nagpure A, Gupta RK (2021) DNA barcoding: a modern age tool for detection of adulteration in food. Critical Reviews in Biotechnology 41: 767–791. https://doi.org/10.1080/07388551.2021.1874279

Ngo HM, Liu R, Moritaka M, Fukuda S (2020) Effects of industry-level factors, brand credibility and brand reputation on brand trust in safe food: evidence from the safe vegetable sector in Vietnam. British Food Journal 122: 2993–3007. https://doi.org/10.1108/BFJ-03-2020-0167

Oh SE, Kim J-H, Kim J-Y, Ahn J-H (2025) Food Safety Distribution Systems Using Private Blockchain: Ensuring Traceability and Data Integrity Verification. Foods 14: 1405. https://doi.org/10.3390/foods14081405

Omar IA, Jayaraman R, Salah K, Simsekler MCE, Yaqoob I, Ellahham S (2020) Ensuring protocol compliance and data transparency in clinical trials using Blockchain smart contracts. BMC Medical Research Methodology 20: 224. https://doi.org/10.1186/s12874-020-01109-5

Onwude DI, Chen G, Eke-emezie N, Kabutey A, Khaled AY, Sturm B (2020) Recent advances in reducing food losses in the supply chain of fresh agricultural produce. Processes 8: 1431. https://doi.org/10.3390/pr8111431

Oriekhoe OI, Oyeyemi OP, Bello BG, Omotoye GB, Daraojimba AI, Adefemi A (2024) Blockchain in supply chain management: A review of efficiency, transparency, and innovation. International Journal of Science and Research Archive 11: 173–181. https://doi.org/10.30574/ijsra.2024.11.1.0028

Oyan O, Şenyüz HH, Arköse CÇ (2024) Comparison of carcass weight and carcass characteristics in some cattle breeds. Research and Practice in Veterinary and Animal Science 1: 1–8. https://doi.org/10.69990/repvas.2024.1.1.1

Patel AS, Brahmbhatt MN, Bariya AR, Nayak JB, Singh VK (2023) Blockchain technology in food safety and traceability concern to livestock products. Heliyon 9: e16526. https://doi.org/10.1016/j.heliyon.2023.e16526

Pavithra T, Rawat S, Sunil CK (2025) Recent trends in blockchain traceability of food products: A review. Food and Humanity 5: 100666. https://doi.org/10.1016/j.foohum.2025.100666

Piorkowski D, Park S, Wang AY, Wang D, Muller M, Portnoy F (2021) How AI developers overcome communication challenges in a multidisciplinary team: A case study. Proceedings of the ACM on Human-Computer Interaction 5: 1–25. https://doi.org/10.1145/3449205

QUT Design Lab (2023) BeefLedger: Blockchain tracking from paddock to plate. https://research.qut.edu.au/designlab/projects/beefledger/ [May 13, 2025]

QUT Design Lab, Cao S, Dulleck U, Powell W, Turner-Morris C, Natanelov V, Foth M, QUT Centre for Behavioural Economics, Society and Technology (BEST) (2020) BeefLedger blockchain-credentialed beef exports to China: Early consumer insights. Queensland University of Technology, New York. https://doi.org/10.5204/rep.eprints.200267

Rabhi A (2024) A blockchain approach for the organic food supply chain. https://doi.org/10.20944/preprints202410.0814.v1

Reddy KRK, Gunasekaran A, Kalpana P, Sreedharan VR, Kumar SA (2021) Developing a blockchain framework for the automotive supply chain: A systematic review. Computers & Industrial Engineering 157: 107334. https://doi.org/10.1016/j.cie.2021.107334

Rebezov M, Khayrullin M, Assenova B, Farida S, Baydan D, Garipova L, Savkina R, Rodionova S (2024) Improving meat quality and safety: innovative strategies. Potravinarstvo Slovak Journal of Food Sciences 18: 523–546. https://doi.org/10.5219/1972

Reitano M, Pappalardo G, Selvaggi R, Zarbà C, Chinnici G (2024) Factors influencing consumer perceptions of food tracked with blockchain technology. A systematic literature review. Applied Food Research 4: 100455. https://doi.org/10.1016/j.afres.2024.100455

Rizwan Abid HM, Ur Rahman HU, Khalid N (2025) Emerging trends and applications of cyber security and artificial intelligence tools in detecting food frauds. Food Reviews International, 1–18. https://doi.org/10.1080/87559129.2025.2493738

Sancheti D, Sancheti S, Sanghavi K, Sanghavi M (2022) Development of AI-driven predictive models and IoT-based solutions for enhancing food quality and safety in supply chains. IJFANS International Journal of Food and Nutritional Sciences 11: 3161–3175.

Schwartz M, Marais J, Strydom PE, Hoffman LC (2022) Effects of increasing internal end-point temperatures on physicochemical and sensory properties of meat: A review. Comprehensive Reviews in Food Science and Food Safety 21: 2843–2872. https://doi.org/10.1111/1541-4337.12948

Sedlmeir J, Buhl HU, Fridgen G, Keller R (2020) The energy consumption of blockchain technology: Beyond myth. Business & Information Systems Engineering 62: 599–608. https://doi.org/10.1007/s12599-020-00656-x

Shen Y, Zhao S, Lv Y, Chen F, Fu L, Karimi-Maleh H (2025) Large language model-driven knowledge discovery for designing advanced micro/nano electrocatalyst materials. Computers, Materials & Continua 84: 1921–1950. https://doi.org/10.32604/cmc.2025.067427

Song JG, Kang ES, Shin HW, Jang JW (2021) A smart contract-based P2P energy trading system with dynamic pricing on ethereum blockchain. Sensors 21: 1985. https://doi.org/10.3390/s21061985

Staci Americas (2024) The role of AI in predictive analytics for supply chain management. https://www.staciamericas.com/blog/the-role-of-ai-in-predictive-analytics-for-supply-chain-management [May 13, 2025]

Steve (2021) Blockchain platform developed by JBS launched to accelerate traceability of entire cattle production chain. JBS Global UK. https://www.jbsglobal.co.uk/2021/04/blockchain-platform-developed-by-jbs-launched-to-accelerate-traceability-of-entire-cattle-production-chain/ [May 13, 2025]

Team (2017) The 7 stages of beef cattle production. Alberta Cattle Feeders' Association. https://cattlefeeders.ca/the-7-stages-of-beef-cattle-production/ [May 13, 2025]

Tegeltija S, Dejanović S, Feng H, Stankovski S, Ostojić G, Kučević D, Marjanović J (2022) Blockchain framework for certification of organic agriculture production. Sustainability 14: 11823. https://doi.org/10.3390/su141911823

Treiblmaier H, Garaus M (2023) Using blockchain to signal quality in the food supply chain: The impact on consumer purchase intentions and the moderating effect of brand familiarity. International Journal of Information Management 68: 102514. https://doi.org/10.1016/j.ijinfomgt.2022.102514

Wahyuni HC, Rosid MA, Azara R, Voak A (2024) Blockchain technology design based on food safety and halal risk analysis in the beef supply chain with FMEA-FTA. Journal of Engineering Research: S2307187724000294. https://doi.org/10.1016/j.jer.2024.02.002

Wang L, Xu L, Zheng Z, Liu S, Li X, Cao L, Li J, Sun C (2021) Smart contract-based agricultural food supply chain traceability. IEEE Access 9: 9296–9307. https://doi.org/10.1109/ACCESS.2021.3050112

Wüst K, Matetic S, Egli S, Kostiainen K, Capkun S (2020) ACE: Asynchronous and Concurrent Execution of Complex Smart Contracts. In: Proceedings of the 2020 ACM SIGSAC Conference on Computer and Communications Security. ACM, Virtual Event USA, 587–600. https://doi.org/10.1145/3372297.3417243

Yadav P, Sharma S, Muzumdar A, Modi C, Vyjayanthi C (2022) Designing a Trustworthy and Secured House Rental System using Blockchain and Smart Contracts. In: 2022 IEEE 19th India Council International Conference (INDICON). IEEE, Kochi, India, 1–6. https://doi.org/10.1109/INDICON56171.2022.10039764

Yang Y, Lin M, Lin Y, Zhang C, Wu C (2025) A survey of blockchain applications for management in agriculture and livestock internet of things. Future Internet 17: 40. https://doi.org/10.3390/fi17010040

Zanetoni HHR, Queiroz DM de, Chizzotti ML, Mendonça RD, Baêta F da C, Coelho AL de F, Nacif JAM (2024) Blockchain applied to the traceability of animal products: a systematic literature review<-sup/>. Revista Ciência Agronômica 55: e20238702. https://doi.org/10.5935/1806-6690.20240033

Zhang C, Gong Y, Brown S, Zhang C, Gong Y, Brown S (2023) Case Analysis: BeefLedger. Blockchain Applications in Food Supply Chain Management, 99–139. https://doi.org/10.1007/978-3-031-27054-3_4